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APTIME: Additive Process Technology Integration with Management and Entrepreneurship

Intellectual output 5: Polymer & 3D Printing – Technologies and Applications

une plateforme d'innovation ESTIA INSTITUTE OF TECHNOLOGY | CCI BAYONNE PAYS BASQUE

UNIVERSIDAD REY JUAN CARLOS MCMXCVI

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UNIVERSITY OF WOLVERHAMPTON

Fontys

Program

1) Introduction to Polymer 3D printing by Dr Pierre Michaud
2) Polymer 3D printing, technologies, and applications – Pierre Diaz
3) Polymer 3D printing – Environment & recyclability – Victor Moneuse
4) Practical work Fab lab ESTIA 3: design, CAO, printing – Pierre Diaz, Victor Moneuse (ESTIA)

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Intellectual output 5:
Introduction to Polymer 3D printing

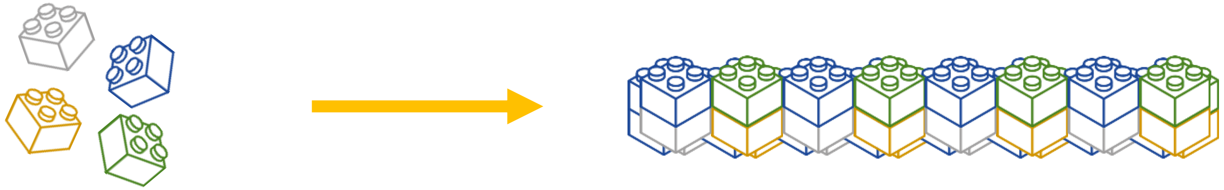
1. What is a Polymer ?
2. Type of polymers: Thermoset / Thermoplastic / Elastomers
4. Tg, Tf & mechanical and thermal properties
5. Applications (main examples per type of polymer)

Introduction

• What is a polymer ?

A polymer is a **macromolecule**, i.e. a large molecule, consisting of a large number of units linked by covalent bonds.

The molecules from which the motifs are derived are called **monomers**.



Monomer

Copolymer

Polymerization is the reaction which, from monomers, forms macromolecules by binding them.

To **represent** a polymer, we put the pattern in parenthesis and add in index *n*.

A **copolymer** is a polymer that has monomer units of two or more different kinds.

A **homopolymer** is a polymer that has identical monomer units.

The polymers can be of **natural** (animal or vegetable) or **synthetic** origin.

Introduction

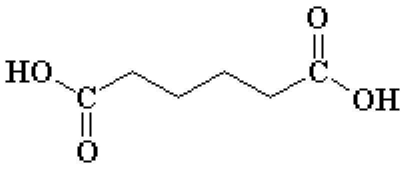
How is a polymer formed ?

Polymerization can be done in two different ways: **step polymerization** and **chain polymerization**.

Polymerization by step

Two different reactions can be involved with stepwise polymerization: **polycondensation** and **polyaddition**

Polycondensation



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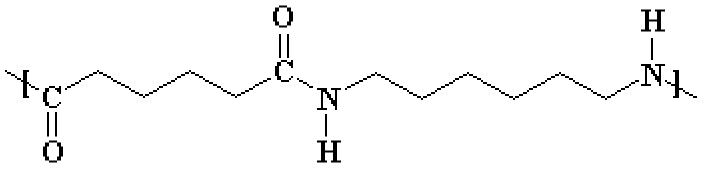
Adipic acid

Hexamethylene diamine

Release of H2O molecules



Polyamide 6-6 (Nylon 6-6)

During a polycondensation reaction, a small molecule is released at each step (water, HCl, OH, ...)

Introduction

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Polymerization by step

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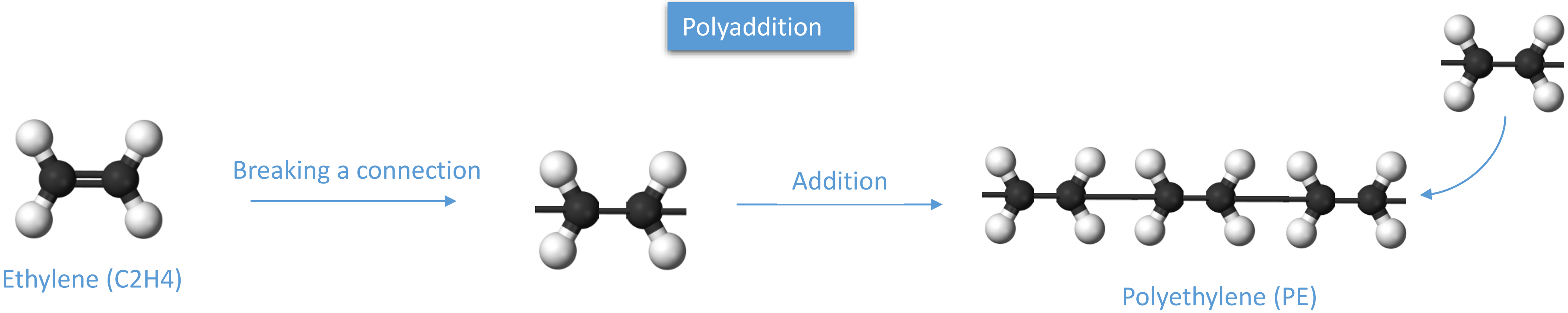
Polyaddition



In a **polyaddition** reaction, **no small molecules are released**, all the atoms of the monomer are in the polymer.

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How is a polymer formed ?

Polymerization can be done in two different ways: **step polymerization** and **chain polymerization**.

Chain polymerization

Two different reactions can be involved in **chain polymerization**: **radical polymerization** and **ionic polymerization**.

Mecanism

- **Initiation:** activation of the monomer with an **initiator**.

  A + M → M*   M* is the activated monomer or active center

- **Propagation** : propagation of the active center to other monomers.

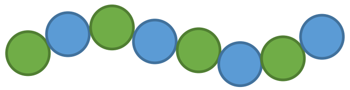
  M* + M → MM*
  MM* + M → MMM* …

- **Termination:** deactivation of the active center.

  Mn* → Mn

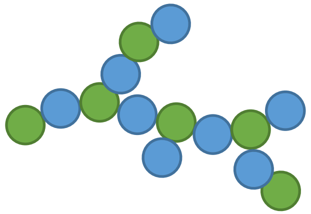
Macromolecular structure

Linear polymers



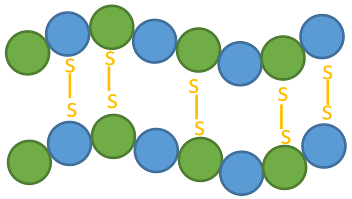
Consisting of large chains of monomers arranged in a straight line. These macromolecules are linked together by secondary bonds (bonds, or hydrogen bridges or Van der Waals bonds) which ensure stability.

Branched polymers



Homopolymeric or copolymeric chains can be grafted onto other chains during polymerization.

Three-dimensional polymers



Chemical bonds in different spatial directions are formed during polymerization and form a network.

Morphologies

Amorphous state

(non-oriented)

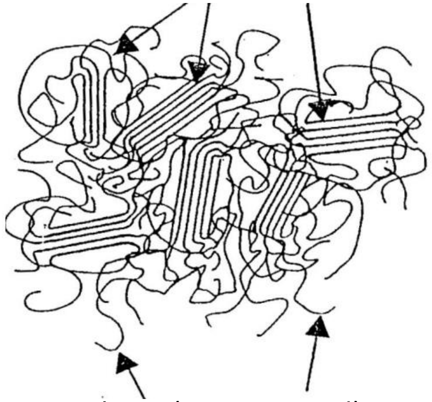
Lack of order: statistical ball

Characterized by :

- Presence of a thermal transition: **Tg**
- **Transparency**: more than 92% transmission in the visible
- Low chemical resistance

Semi-crystalline state

Crystalline zones (oriented)



Amorphous (non-oriented) zones

Alignment of the chains against each other

Characterized by :

- **Two** phase transitions:
  - → Tf for crystalline part
  - → Tg for amorphous part
- Translucent: low light transmission by diffusion
- Better chemical resistance

Polymer classification

Thermoplastics

The polymer chains are linear or branched and linked together by weak bonds (hydrogen or Van der Waals).

At low temperatures the weak bonds limit the mobility of the chains, which gives a solid behavior to the polymer.

Upon heating, the bonds break and the polymer softens, giving the polymer the behavior of a thick fluid.

Reversible

Potentially recyclable

Thermosets

The chains are cross-linked and linked in space by strong covalent bonds.

Thermosets can only be processed once and become insoluble and infusible after polymerization.

The polymerization is **irreversible.**

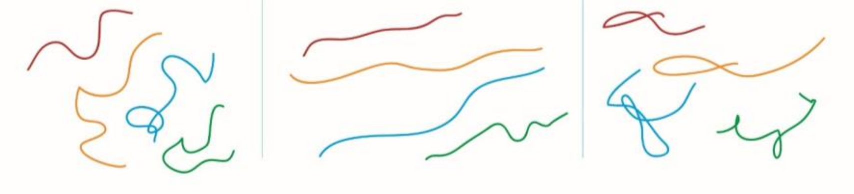
Difficult to recycle

Elastomers

Commonly called "rubbers". The chains are cross-linked.

It is a low cross-linked polymer with a **high elongation** at break (>100%).

The elastomers are already softened at the operating temperature in the non-crosslinked areas.



Elastomer at rest | Stretched elastomer | Elastomer after stretching

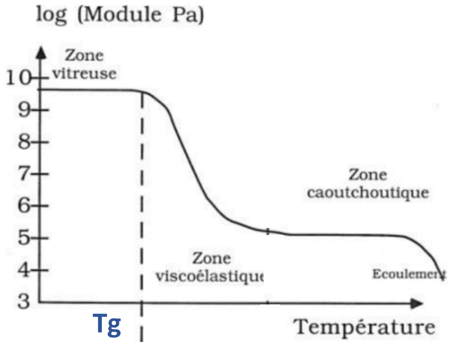
Focus on thermoplastics

Semi-Crystalline :

Amorphous :

- Amorphous thermoplastic: the polymer chains are arranged in a disordered and random way in space.

- Low force of attraction between the polymer chains
- Low heat resistance
- Faible résistance chimique
- More transparent
- No more deformation
- Easier to implement



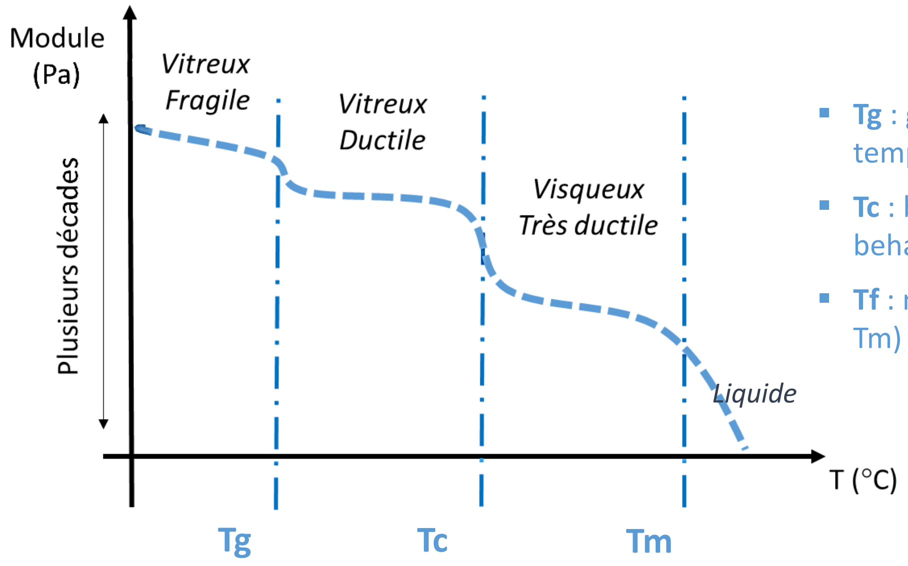
General information :

- 90% of plastic applications.
- Can be remelted and reshaped many times while retaining their properties.
- Easier to manufacture than thermosets.
- Great variety of colors.

- High creep.
- High coefficient of linear expansion.

- Crystal structure: the molecular structure is **ordered**.
- A polymer can not crystallize completely, there are always amorphous parts: **semi-crystalline**.

The physical-chemical and mechanical properties of thermoplastics will depend on the degree of crystallinity



- **Tg** : glass transition temperature
- **Tc** : beginning of the rubber behavior
- **Tf** : melting temperature (or Tm)

- T < Tg : **glassy**, hard and fragile state
- Tg < T < Tc : **viscoelastic** state
- Tc < T < Tf : **rubbery** state
- T > Tf : **liquid** state

No viscous state for Thermo-sets and elastomers

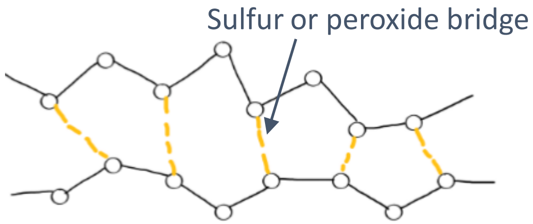
The shaping of thermoplastics is done in a rubbery state

Focus on elastomers

General information :

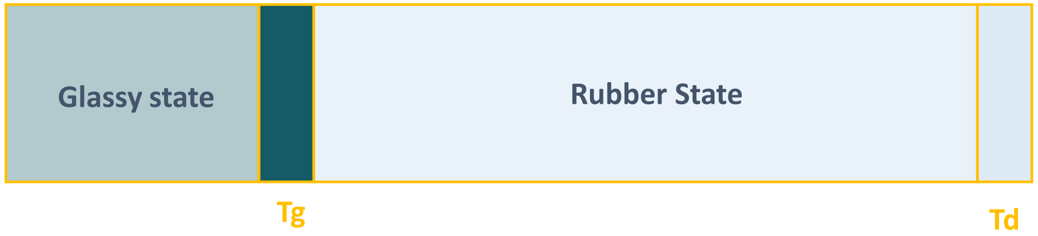
- Amorphous cross-linked structure.
- High elastic deformation (ability to stretch elastically up to 1000%).
- Low modulus (low stiffness).
- Insoluble and infusible.
- Appearance of injectable thermoplastic elastomers (TPE).

Propriétés



Elastic

- Three-dimensional structure formed by vulcanization.
- Covalent bonds between the chains.
- Low cross-linking density.



Properties for T > Tg

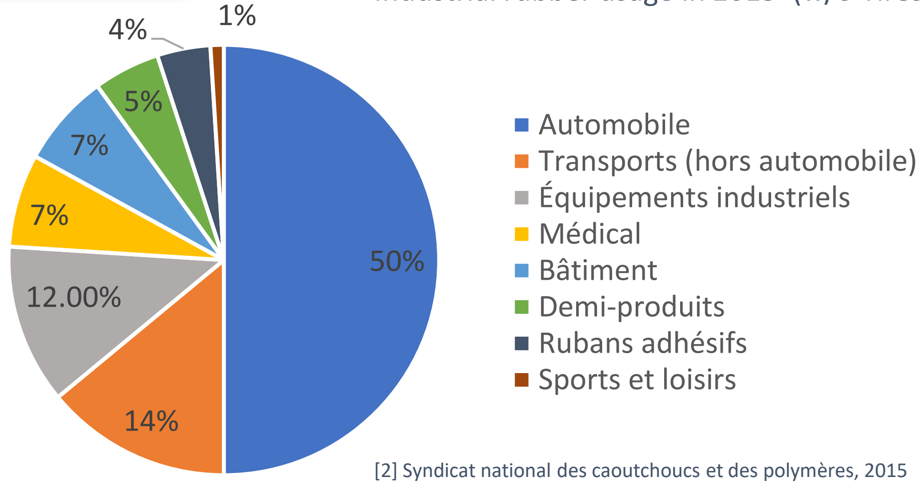
- Good flexibility.
- High reversible elasticity.

ETP

Combine the elasticity performance of vulcanized elastomers with the easy shaping and reusability of TP.

Applications :

Industrial rubber usage in 2015 (w/o Tires) [2]



[2] Syndicat national des caoutchoucs et des polymères, 2015

The plastics

- A plastic is a material made of synthetic or semi-synthetic compounds that has the property of being capable of changing its shape

- Most plastics on the market are derived from petrochemicals.

- However, given the growing environmental concern, plastics derived from renewable materials such as Polylactic Acid (PLA) are also popular.

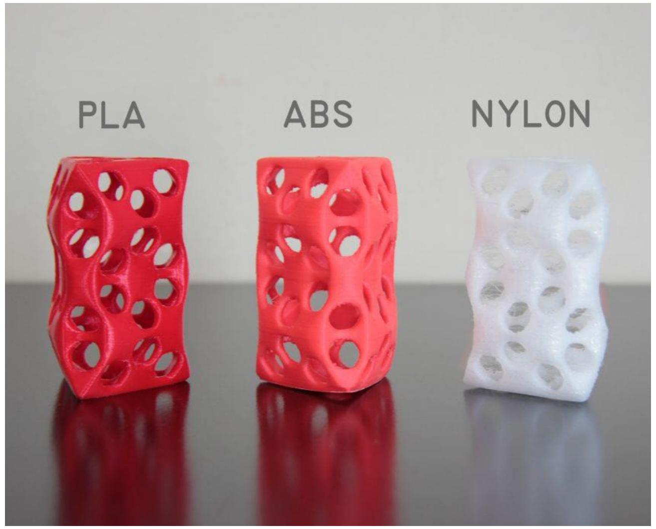
- Due to their low cost, ease of manufacture, versatility and water resistance, plastics are used in a multitude of products and sectors. In the AM sector, 3D printing plastics are also developed

- Depending on the way they are polymerized and the form they have as raw material, different technologies can be applied to put them in form

ABS : Acrylonitrile Butadiene Styrene

- **ABS** filament is the **most commonly used** 3D printing plastics.
- It is a thermoplastic which contains a base of elastomers based on polybutadiene, making it more flexible, and resistant to shocks.
- **ABS** can also be found in powder form for powder bed processes such as SLS, and liquid form for SLA and PolyJet technologies.
- **ABS** is used in 3D printing when heated between 230°C and 260°C. It is a tough material, able to easily withstand temperatures of -20°C to 80°C. In addition to its high strength, it is a reusable material and can be welded with chemical processes. It's a common plastic polymer, it's used to print strong parts. Having a higher glass transition temperature could be used to make parts that are used in hotter environments compared to PLA
- However, **ABS** is not biodegradable and shrinks in contact with air, so the printing platform must be heated to prevent warping. It is recommended to use a closed chamber 3D printer to limit particle emissions when printing with **ABS**, even to use proper aeration and filtration system.

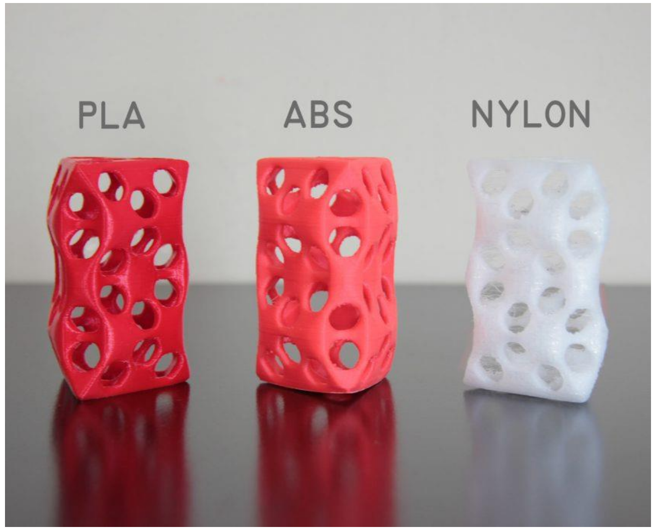
Andrew Sink



https://opentotum.github.io/fabtotum.com-backup/filaments/index.html

PLA : polylactic acid

- **PLA** has the benefit of being biodegradable (coming from corn), unlike ABS.
- **PLA** is manufactured using renewable raw materials such as corn starch.
- **PLA** is one of the easiest materials to print, though it does have a tendency to shrink slightly after 3D printing.
- You don't require a heated platform when printing in **PLA**, unlike with ABS.
- **PLA** also prints at a lower temperature than ABS, between 190°C to 230°C.
- **PLA** has a high cooling and solidification speed. It is also important to mention that models can deteriorate when in contact with water.



PLA vs ABS

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PLA vs ABS: thermal properties

Thermal properties	PLA	ABS
Melt volume index (MVI)	10.3cm^3/10min	9.7cm^3/10min
Glass transition temperature	60-65ºC	105ºC
Slumping temperature	70-80ºC	110-125ºC
Melting temperature	160-190ºC	210-240ºC
Printing temperature	190-220ºC	230-250ºC
Recommended printbed temperature	50-70ºC (heated bed not mandatory)	80-120ºC (heated bed required)

ASA : Acrylic-styrene-acrylonitrile

- **ASA** is a material that has similar properties to ABS, with a greater resistance to UV
- It is advised to print the material with a heated bed platform to prevent warping.
- When printing with **ASA**, similar print settings are used to ABS, but extra care must be taken to print with a closed chamber due to styrene emissions.

Stratasys ©

Stratasys ©

PET : Polyethylene terephthalate

- **PET**, is commonly seen in disposable plastic bottles.
- **PET** is the ideal filament for any pieces intended for contact with food.
- **PET** is fairly rigid and has good chemical resistance.
- To obtain the best results when printing with **PET**, print between 75 – 90ºC.
- **PET** is commonly marketed as a translucent filament, with variants such as **PETG (Glycol modified)**, **PETE**, and **PETT**.
- Advantages of **PET** include that the material doesn't release any odours when printing, and is 100% recyclable.

PETG : glycolized polyester

- **PETG** is a thermoplastic widely used in the additive manufacturing
- **PETG** combines both the simplicity of **PLA** 3D printing and the strength of **ABS**.
- It is an amorphous plastic, which can be 100% recycled.
- It has the same chemical composition as **PET**. Glycol has been added to reduce its brittleness and therefore its fragility.

PC : PolyCarbonate

- **PC** is a high strength material designed for engineering applications.
- **PC** has good temperature resistance, able to resist any physical deformation up to around 150ºC.
- **PC** is prone to absorbing moisture from the air, which can affect performance and printing resistance.
- **PC** has to be stored in airtight containers.
- **PC** is highly valued by the AM industry for its strength and transparency.
- **PC** has a much lower density than glass, making it particularly interesting for designing optical parts, protective screens or decorative objects.

High Performance Polymers

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- The evolution of 3D printing technologies has led to the development of a whole range of **high-performance filaments** with high mechanical characteristics.

- There are several types of **high-performance 3D printing plastics** such as **PEEK**, **PEKK** or **ULTEM** – they are distinguished by family such as polyaryletherketones (PAEK) or polyetherimides (PEI).

- These filaments have a **very high mechanical and thermal resistance**, are very strong and at the same time much lighter than some metals. These properties make them very attractive in the aerospace, automotive and medical sectors.

- Due to their characteristics, high performance polymers **cannot be printed on all FDM machines** on the market. Indeed, the 3D printer must have a heating plate capable of reaching at **least 230°C**, an **extrusion at 350°C** and a closed chamber.

- About 65% of these materials are printed with **FDM technology**, but they are also found in powder form, compatible with **SLS technology**.

PEEK : Polyether ether ketone

- **PEEK**, is a semi-crystalline thermoplastic that is well known in the manufacturing industry for its mechanical properties.

- Mainly used in the aerospace, medical and automotive industries, **PEEK** is heat and wear resistant and can substitute some metals due to its weight-to-strength ratio.

- **PEEK** is difficult to print, requiring a number of parameters to be met.

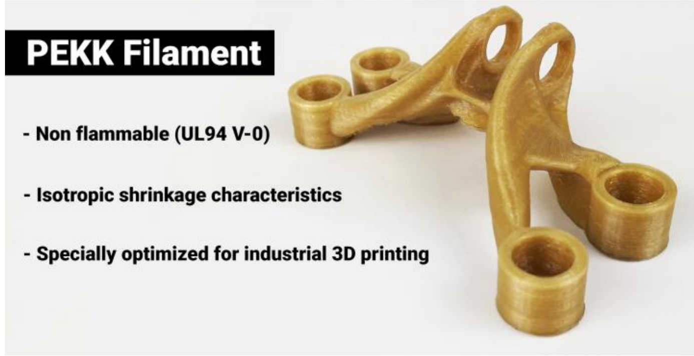
- **PEEK** is a member of the **PAEK** (polyaryletherketone) family, which is known for its high thermomechanical properties.

- It is a semi-crystalline polymer, therefore when it melts, its molecules arrange themselves under the effect of heat, creating a certain order until the material solidifies completely. This enables it to maintain its mechanical characteristics when the temperature is increased. While this semi-crystalline structure has many advantages, it should be noted that in additive manufacturing, it involves a more complex printing process

https://3dgence.com/

PEKK : Polyetherketoneketone

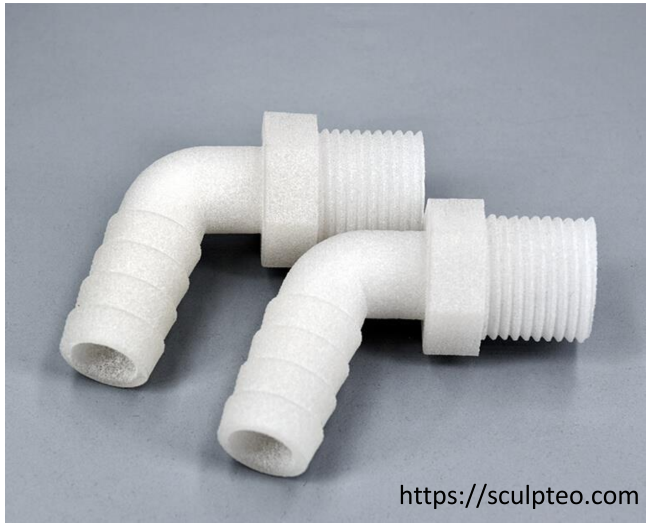
- **PEKK** is a semi-crystalline thermoplastic. Often compared to PEEK, it belongs to the same family – the PAEK family – known for its mechanical and chemical properties.
- Easier to print than PEEK, in particular thanks to its lower crystallisation rate
- Exists in filament for high temperature machine but also as powder for SLS machines.
- However, it is still a very technical and expensive material, mostly used in demanding industries such as aerospace or Oil & Gas.
- The main difference with PEEK is the ether/ketone ratio: **PEKK** has more ketone bonds, which are more flexible than ether bonds. In particular, this increases the rigidity of the polymer chains, thus raising the glass transition temperature and the melting temperature. Note also that this ratio is not the only difference.



https://www.3d4makers.com/

Before Annealing After Annealing

PP: Polypropylene



- **PP** is another thermoplastic widely used in the automotive sector, professional textiles sector, and in the manufacturing of hundreds of everyday objects.

- **PP** is resistant to abrasion, has good ability to absorb shocks, as well as relative rigidity and flexibility.

- However, drawbacks of the material include its low temperature resistance, and sensitivity to UV rays.

- Due to this, several manufacturers have developed alternative types of PP, simili-propilenos, that are stronger both physically and mechanically.

Nylon: Polyamides (PA)

- Objects made from **polyamides** (nylon) are usually created from a fine, white, granular powder with SLS technology.

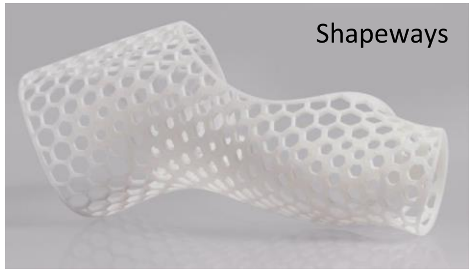
- There are however some variants of the material such as nylon that are also available in filaments used in fused deposition modeling (FDM). Due to its biocompatibility, **polyamides** can be used to create parts that come into contact with food (except foods that contain alcohol).

- Constituted of semi crystalline structures, **polyamides** have a good balance of chemical and mechanical characteristics that offer good stability, rigidity, flexibility, and shock resistance.

- **PA** are classified according to their chemical composition, and in particular according to the number of carbon atoms they contain:
  - The most used in 3D printing are : PA12 and PA11, as well as PA6 for FDM.

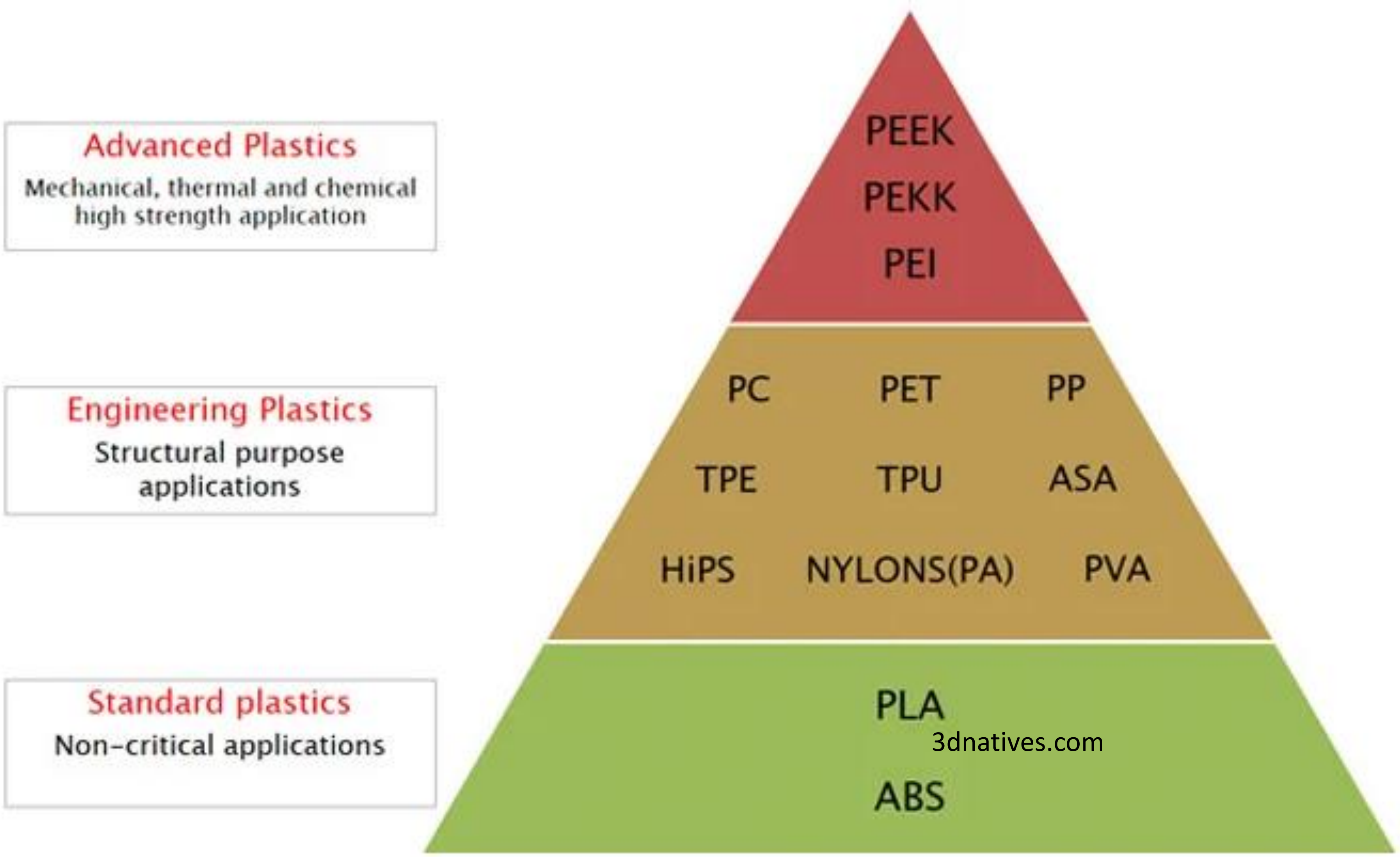
- Due to its high quality, **polyamides** are used in the manufacture of gears, parts for the aerospace market, automotive market, robotics, medical prostheses, and injection molds.

Shapeways



Shapeways

Classification



Resins – Photopolymerization technologies

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- 3D printing technologies based on photopolymerization use **UV-sensitive resins** to create objects layer by layer.
- They use a light source such as a laser or LCD screen to solidify a **liquid photopolymer**.
- Technologies include SLA, DLP, and even Material Jetting (PolyJet). Creating parts using resins results in **high detail and smooth surface objects**, nevertheless, the color range is still quite limited using this process.
- Standard resin has properties similar to ABS: the surface finish of the part will be good given the photopolymerization process, however mechanical properties will be moderate.
- More advanced resins do exist for technical applications such as in dentistry (also need to be biocompatible), or engineering.
- Over the years, manufacturers have expanded their range of liquid photopolymers to answer manufacturing needs from various sectors. Therefore, you should be able to find resins that have high-temperature resistance, can withstand large impacts, or that have high elongation properties.

Silicone

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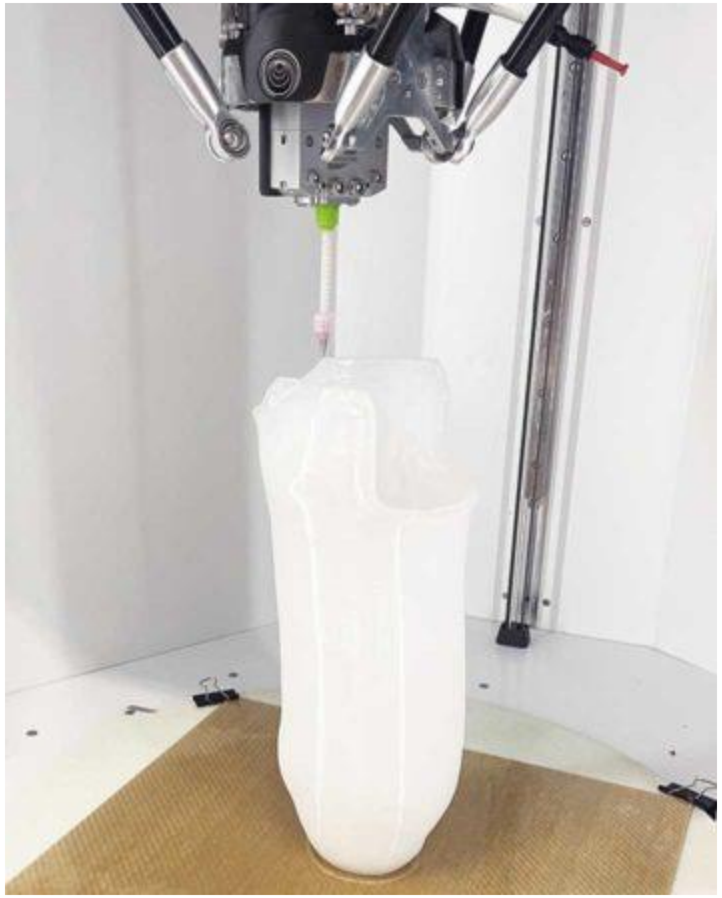
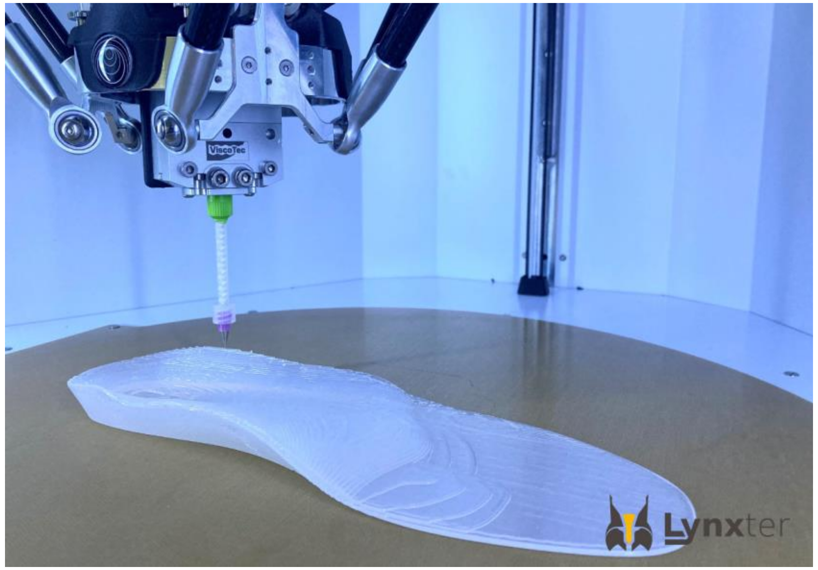




You will see good examples on Friday’s visit !

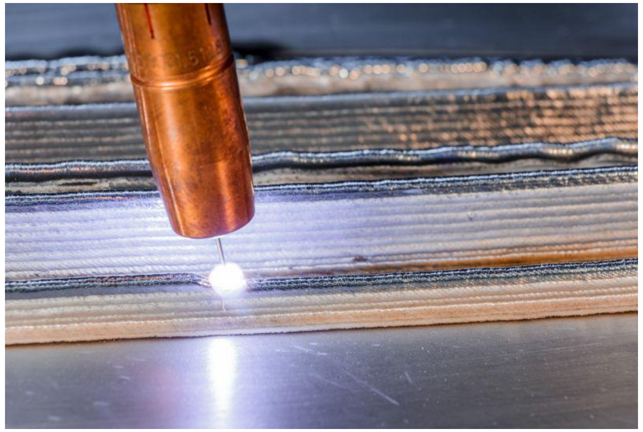
APTIME: Additive Process Technology Integration with Management and Entrepreneurship

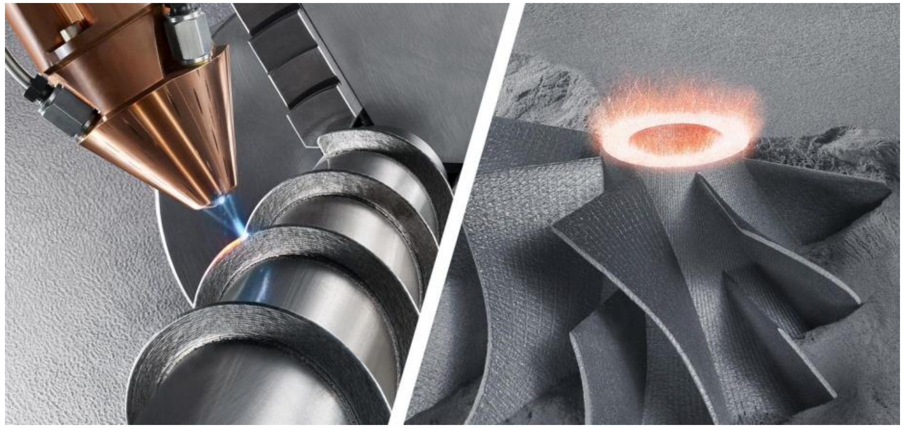
Intellectual output 5: Polymer 3D printing Technologies & Applications

Additive Manufacturing: Definition

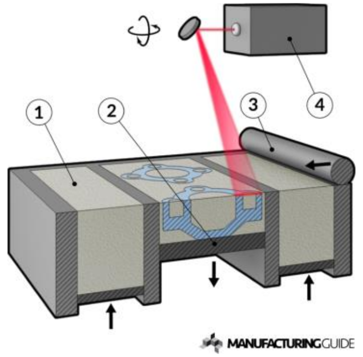
- Additive manufacturing refers to manufacturing processes by adding material, most of the time computer-assisted. It is defined by ASTM as the process of shaping a part by adding material, by stacking successive layers, as opposed to processes by removing material, such as machining.

- The term is synonymous with three-dimensional printing or 3D printing which are general public names. Additive Manufacturing is a terminology used in the industrial world.





Additive Manufacturing: Historical



- 1971 : First AM patent by Pierre Ciraud: Production of 3D parts from a material in powder and laser form for the temperature rise.

- 1984 : SLA stereolithography patent by Charles Hull (US4575330), Jean Claude André, Alain Le Méhauté and Olivier de Witte. Co-founder of 3D Systems.

- 1987 : First commercial 3D Systems machine

- 1995 : First metal machine: EOS, DTM (3D Systems) : EOSINT M250

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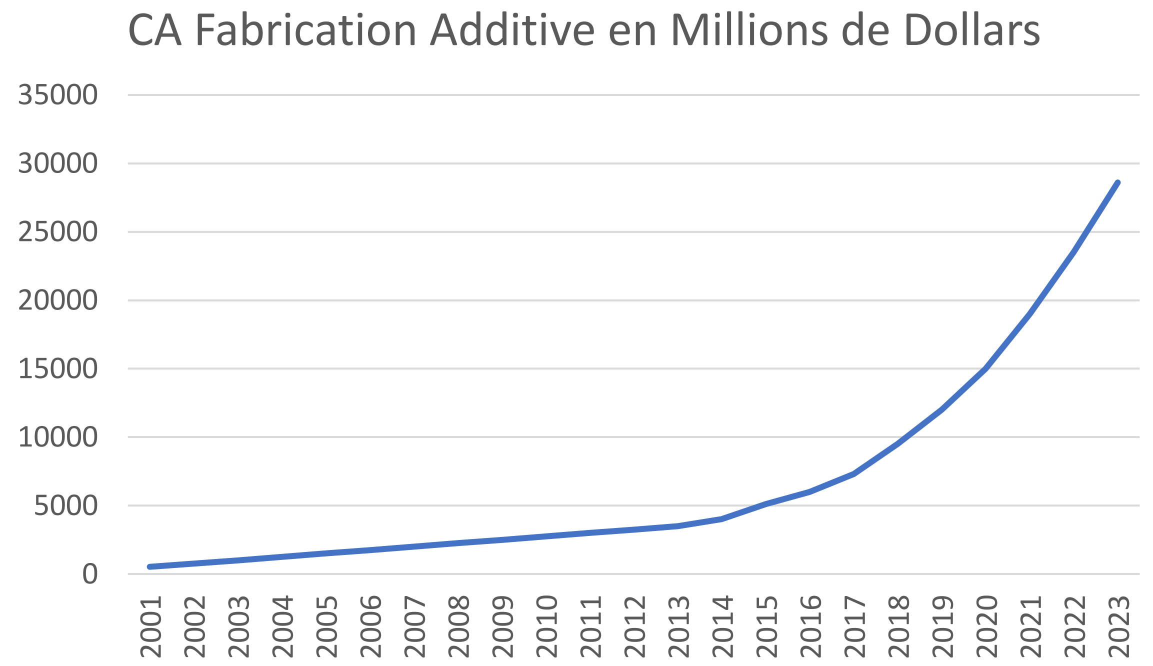
Additive Manufacturing: Market

❖ Strong growth in overall turnover:

538 M$ in 2001, 7300M$ in 2017, 11800M€ in 2019 and perspective to 28600M$ in 2023

- 50% products : Machines, raw material, softwares, etc.
- 50% services : Manufacturing, research, consulting, maintenance



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Additive Manufacturing: Market

- A booming sector where the degree of adoption and maturity vary according to uses and applications
- Disruption of value chains / New possibilities
- Technologies in constant development
- 80% increase in machine sales in 2017

Polymers: Some numbers

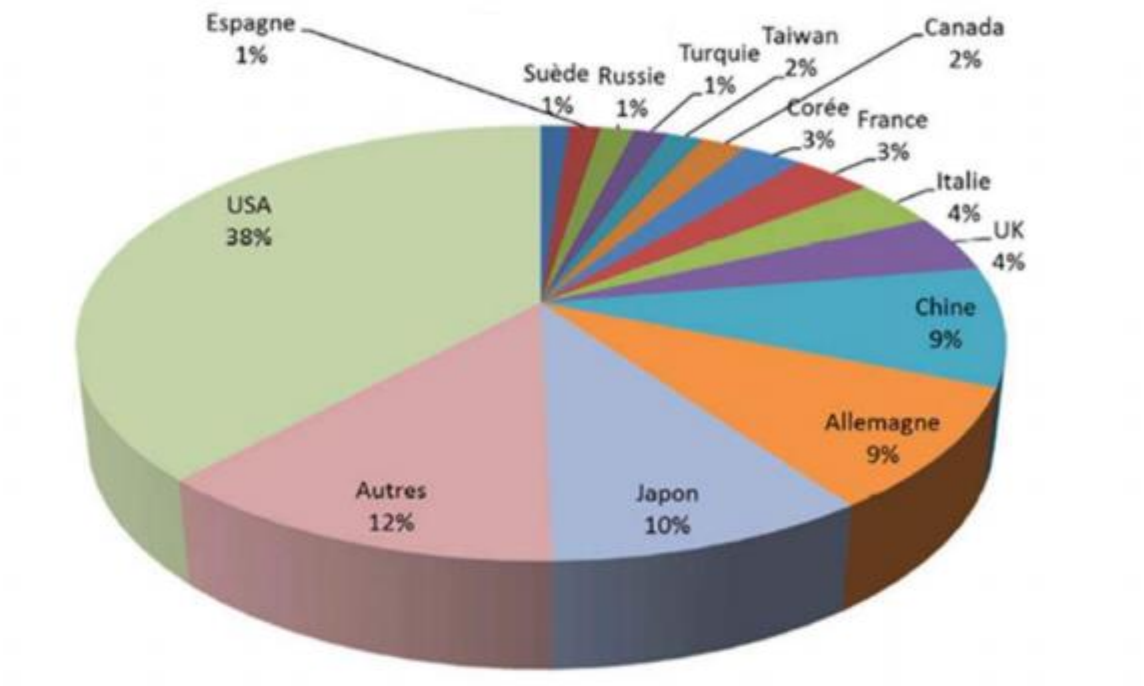
- 12 850 « Industrial » machines sold in 2014
- 163 999 « 3D Printers » sold in 2014
- 278 385 « 3D Printers » sold in 2015

Metal : Some Numbers

- 550 machines sold in 2014
- 808 machines sold in 2015
- 982 machines sold in 2016
- 1768 machines sold in 2017 (+80% increasing)
- 2327 machines sold in 2019 (213 referenced manufacturers by Wohlers)

Additive Manufacturing: Market

- France represents only 3% of the world park against 38% for the United States



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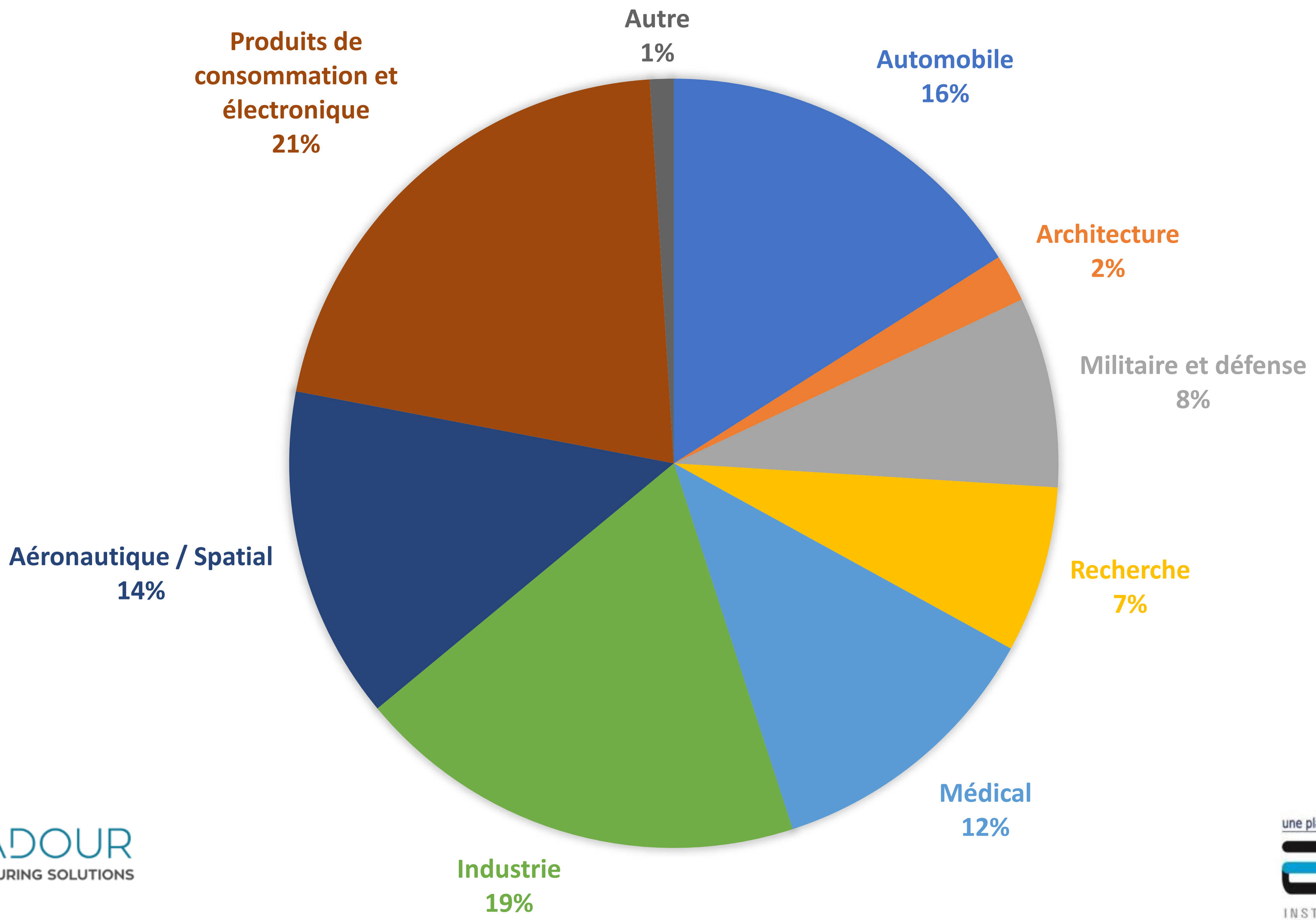
Additive Manufacturing: Market (2014)



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3D printing Market

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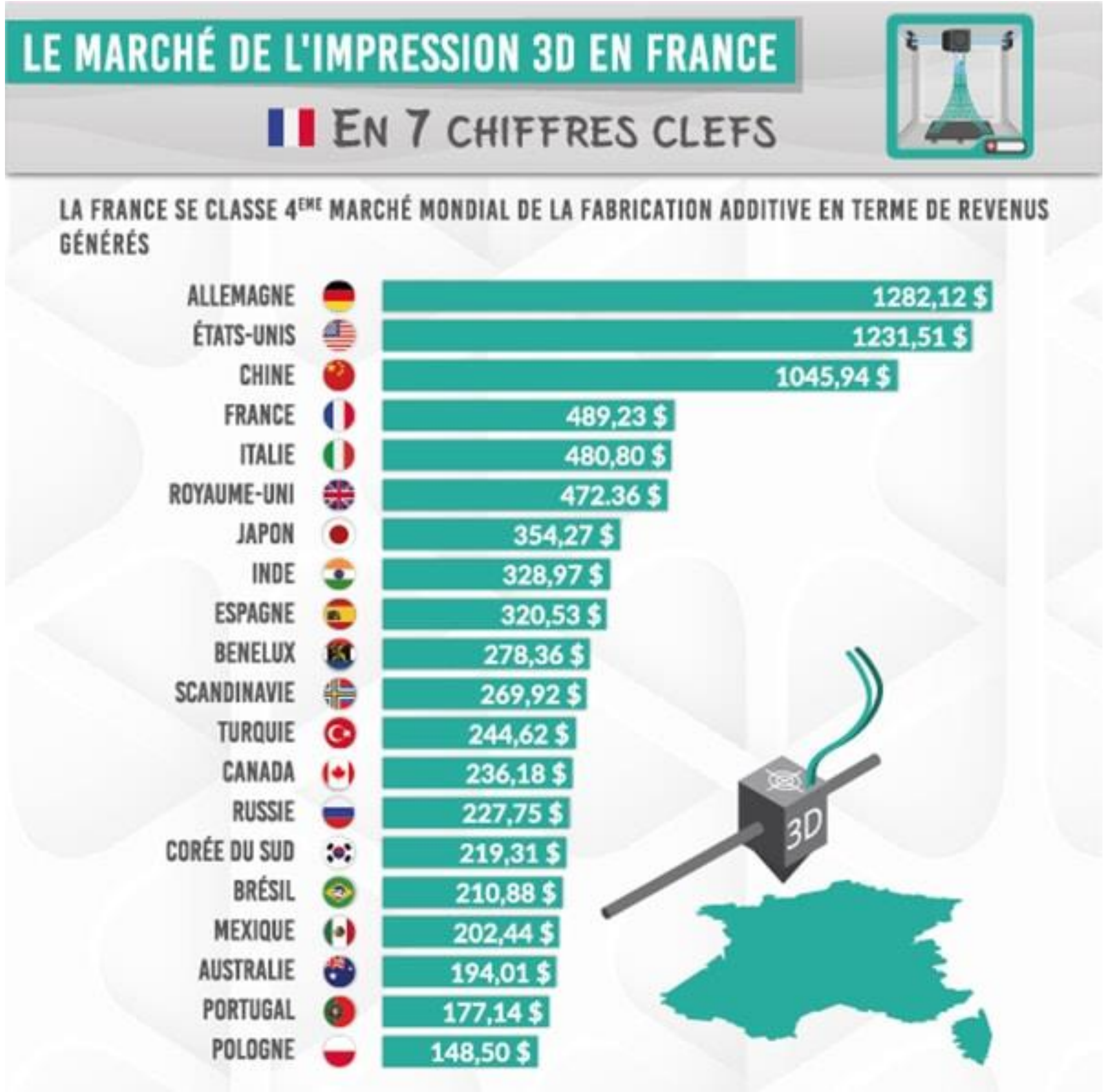
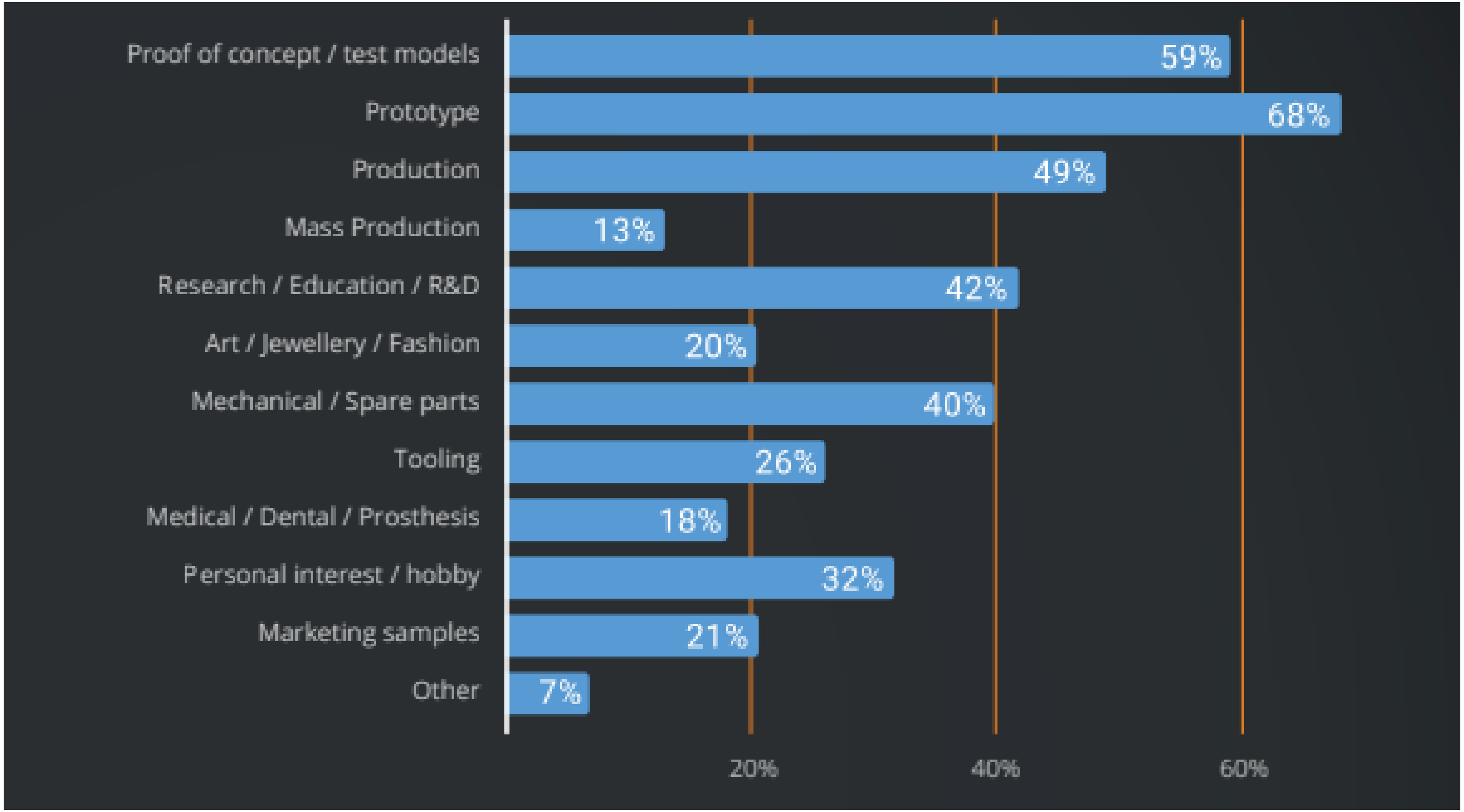


3D printing Market



Beware of general information on Additive Manufacturing

- Cost reduction (recurring and non-recurring: no tools)
- Reduction of the production cycle
- Design flexibility
- Reduction of the environmental impact
- Raw material reduction

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- Mechanical performance (Roughness, porosities, precision, material anisotropy, high residual stresses, etc.)
- Almost compulsory post-processing after manufacture
- Controllability of limited parts
- Cost sometimes much higher than conventional processes
- Environmental impact: recyclability of powders

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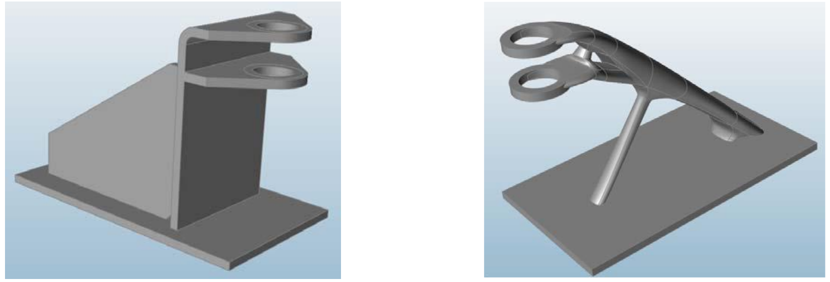
- Environmental impact: recyclability of powders

Each study is unique and depends on the technologies, the type of parts, the size of the series, the complexity, the material, etc.

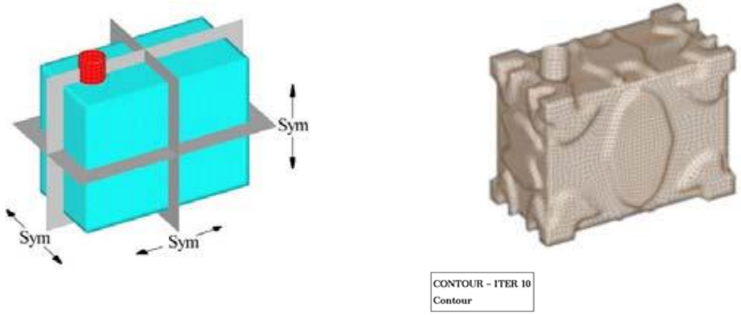
Optimization



Several types of possible optimizations

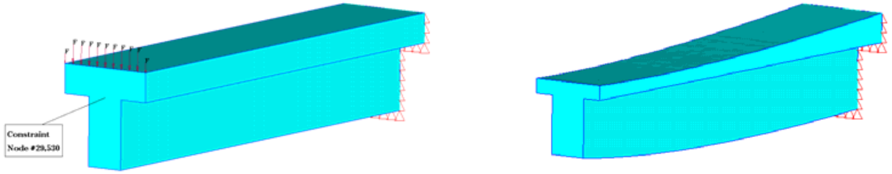
Topological Optimization

Best distribute the distribution of material in a given space.



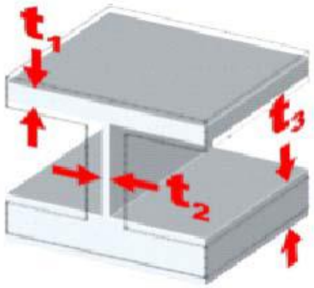
- Topographic Optimization

  Variable shape optimization on a surface type area.



- Shape Optimization

  Modification of an initial shape to find the optimal shape.



- Parametric Optimization

  Automatic modification of the parameters (thickness, material properties, etc.) of a structure to determine the optimal shape.

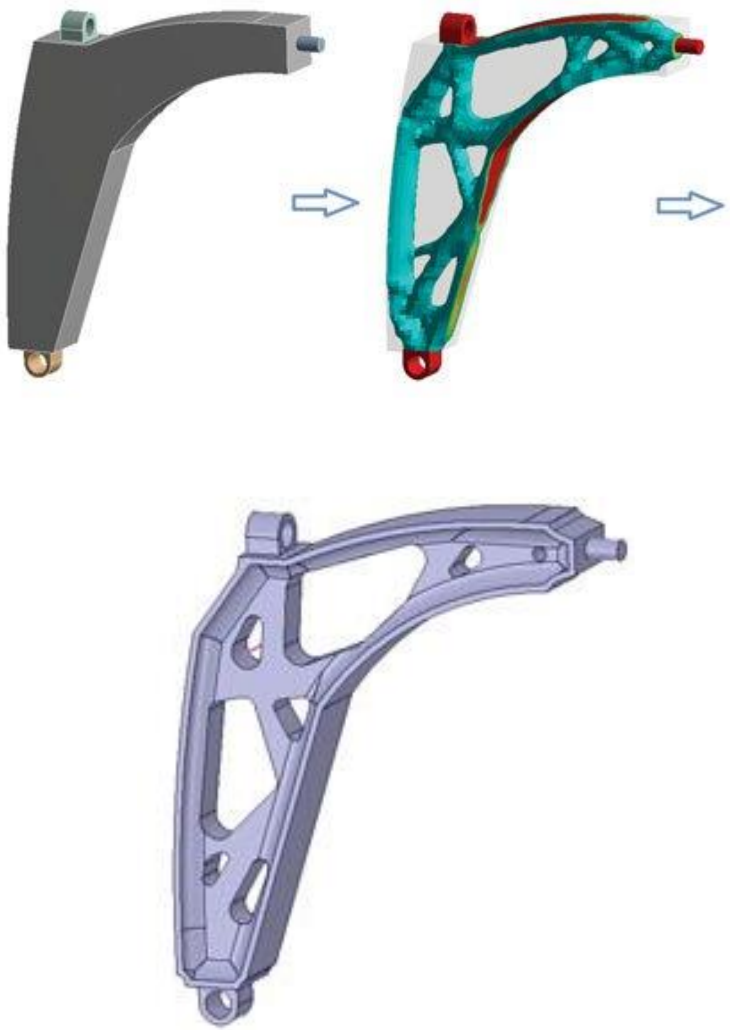
Topological Optimization

1) Topological Optimization

- Find the best distribution of material for a given loading in a defined design volume in order to achieve an objective (minimize mass, maximize stiffness, etc.).

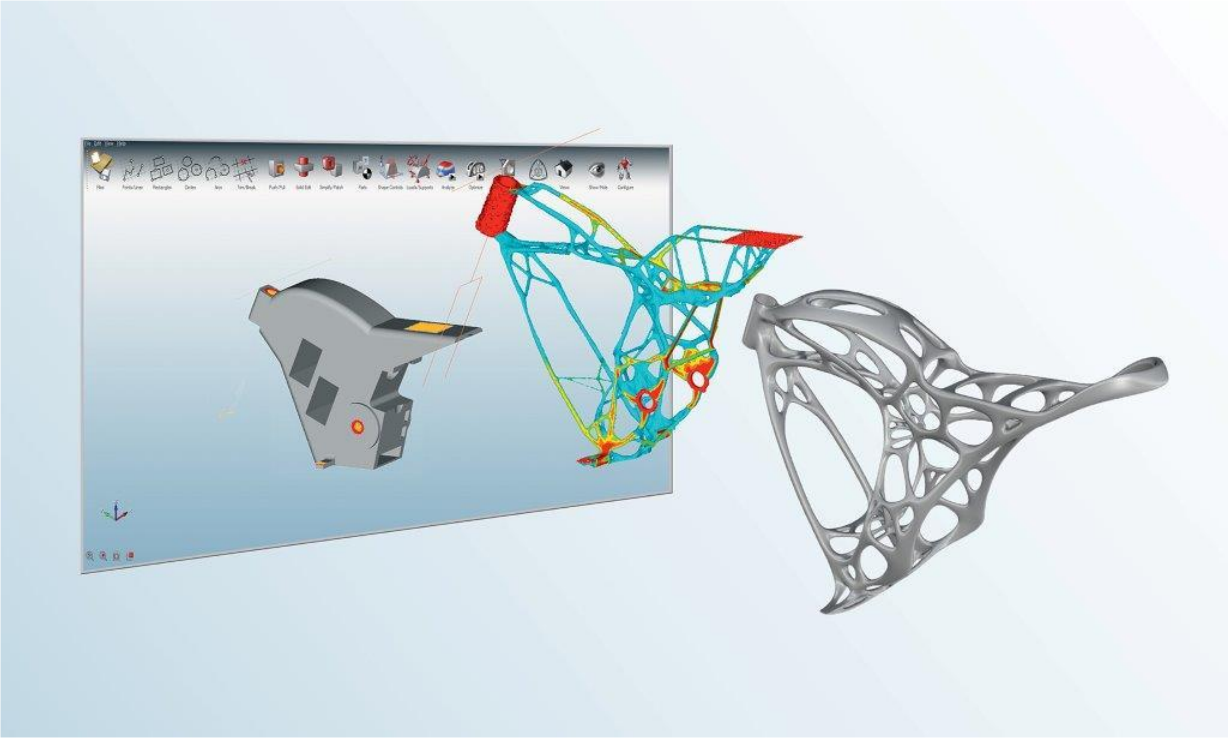
- Topological optimization is a mathematical (finite element) method that optimizes the arrangement of material in a given design space, respecting the given set of loads, boundary conditions and various stresses, with the aim of maximizing system performance.

- In any case, topological optimization is kept at a conceptual level in the design process.. The result must always be interpreted and adapted in order to make it manufacturable.



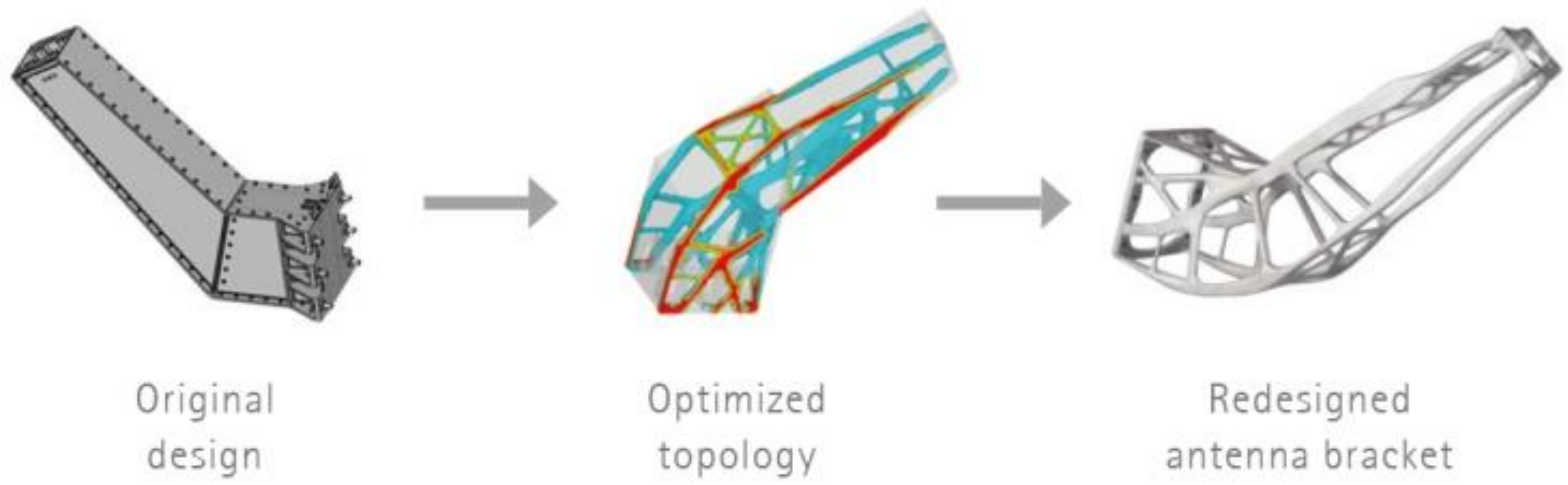
Topological Optimization

Some examples:



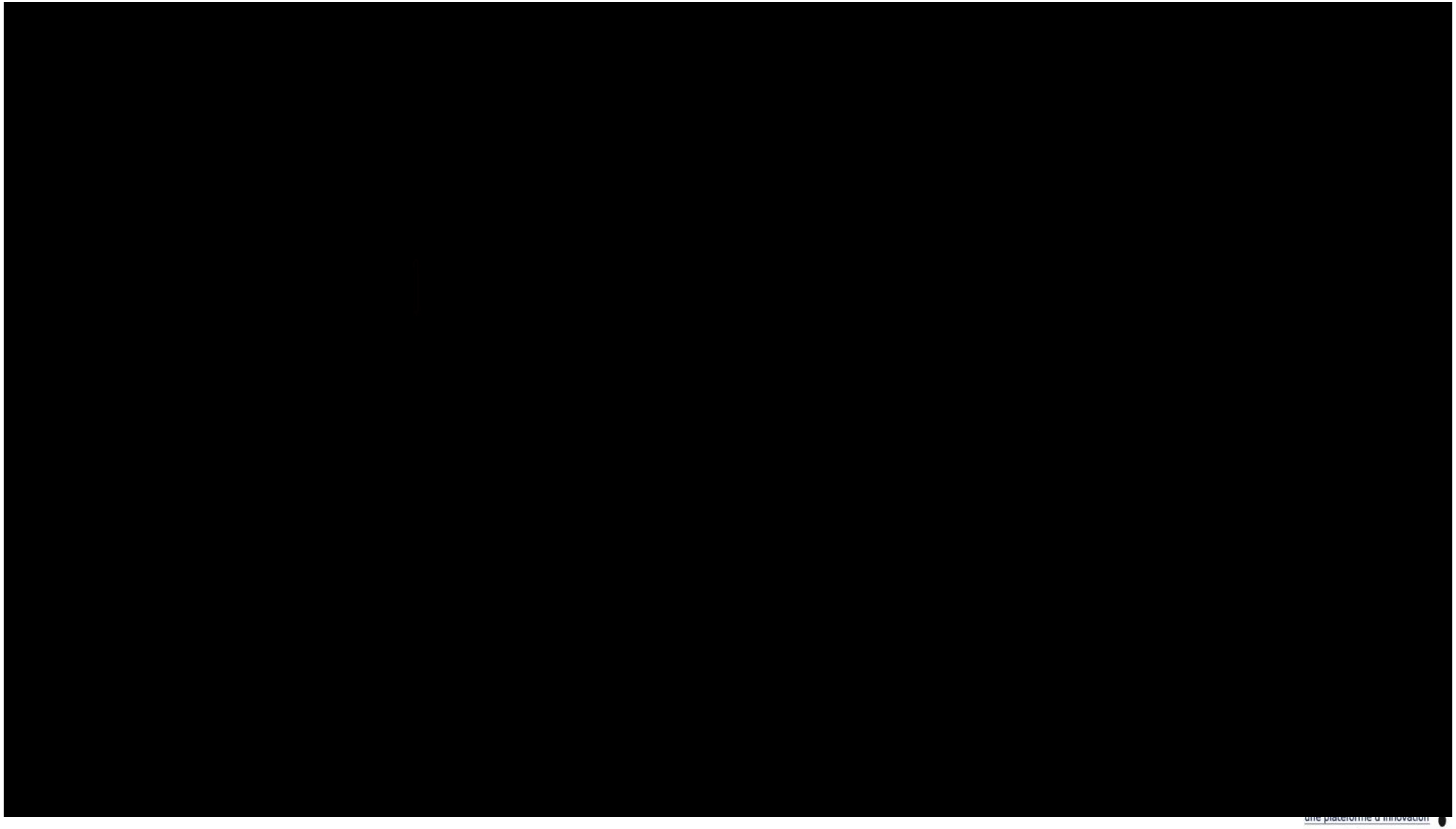
Topological Optimization

Some examples:



https://www.eos.info/case_studies/additive-manufacturing-of-antenna-bracket-for-satellite

Topological Optimization



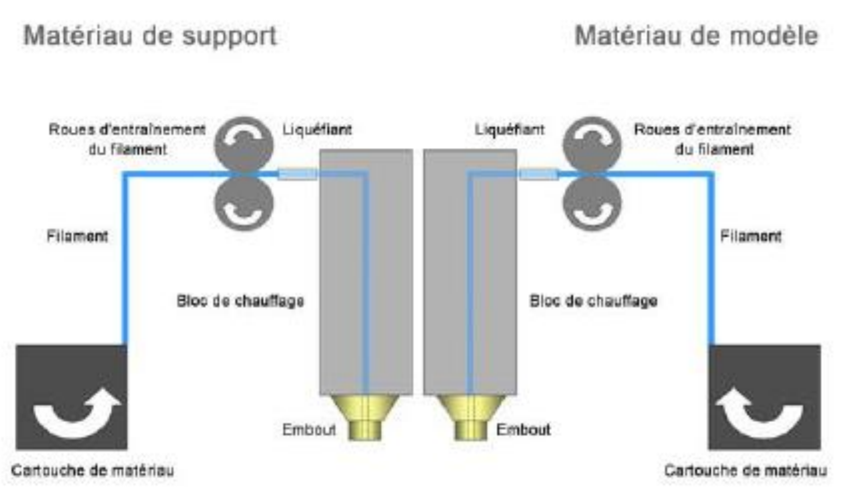
The different AM technologies - Polymers

- Polymers
  - Thermoplastic Extrusion
    - Fused Deposition Modeling (FDM/FFF)
  - Photopolymers
    - Stéréolithography
    - PolyJet
  - Powder
    - Selective Laser Sintering (SLS)
    - Multi Jet Fusion (MJF)
    - Binder Jetting
    - ColorJet

Fused Filament Fabrication (FFF)

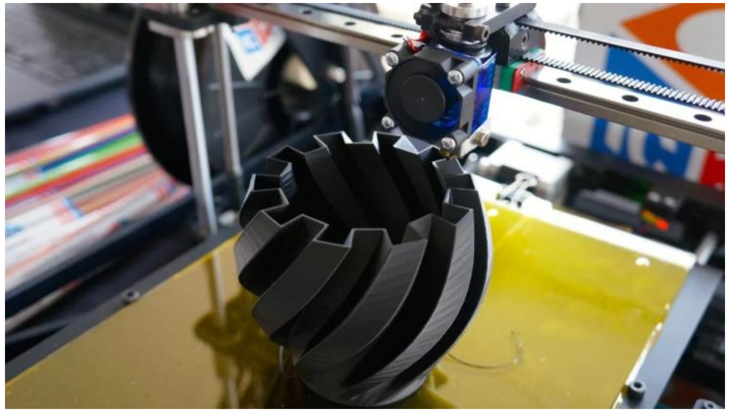
Technology :

Additive manufacturing by deposition of molten material (hot plastic molding) which allows a plastic filament to be melted by heating it via a nozzle (extruder or extrusion head). The stacking of successive layers allows the manufacturing of 3D objects.



Functioning :

- This technology uses plastics such as PLA, ABS, PC, PETG, PEEK, PEKK, etc. generally in the form of filament (1.75 or 2.85mm in diameter) – possibility of having pelet, silicone, ceramic, charged filaments…
- The drive wheels unwind the wire coil
- The heating block brings the temperature of the wire until it melts (approximately 200-400°C)
- The extruder moves while depositing the material
- Double or even triple nozzle possible for printing supports or multi-materials



Fused Filament Fabrication (FFF)

FFF : 3 main types of architecture

1- Cartesian machines :

Advantages : the most common, precise, easy to install. Good ratio between printing speed and final rendering

Inconvenient : inertia, slower kinematics

2- Delta machines

Advantages : More rigid structure, better Jerk, Acceleration and speed

Inconvenient : Often lower print volume, more complex to install / program

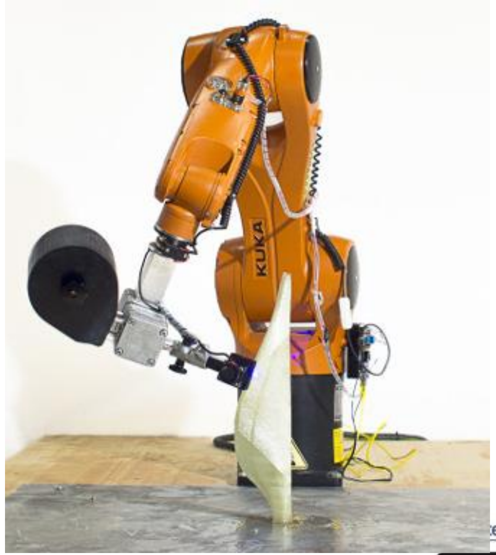
3- Robotized (FFF robotized / FDM Robotized)

Advantages : Very large size (depending the size of the cell), multi axis deposition

Inconvenient : Lack of precision, complexity of programming

https://bentek.fr/axes-imprimante-3d/

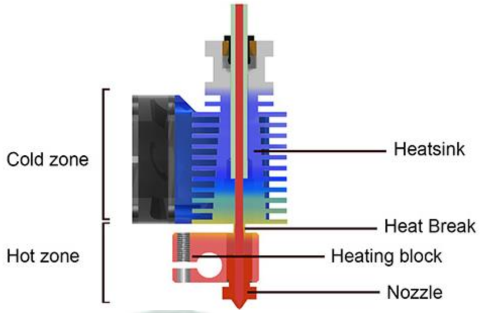
https://www.editions-eni.fr/open/mediabook.aspx?idR=106bec0352ae5b1b73547cf42b621a26



https://www.3dnatives.com/atropos-impression-3d-fibre-de-verre-06042017/

FFF : 3 main types of architecture

The hotend is the element intended to melt the filament so that it can flow through the nozzle, while preventing heat from being transmitted outside the so-called hot zone. The heatbreak serves as a thermal break bridge. Separates the hot zone from the cold zone.



2 main types of material distribution

1- Bowden printing : The extruder stays attached to the frame of the 3D printer and pushes the filament into the hotend through a tube called a Bowden tube.

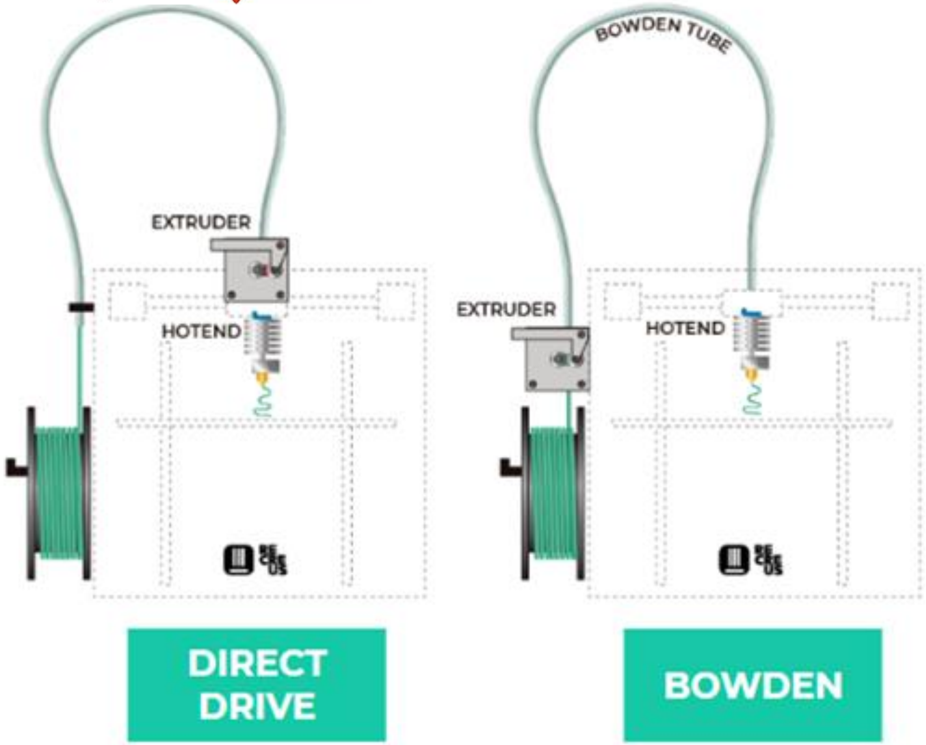
Advantages : High speed – low ghosting – High temperature chamber

Inconvenient : Only rigid material – difficulties to manage retraction

2- Direct drive : The extruder and the hotend form a single element, minimizing the distance between the pull point and the nozzle

Advantages : Better management on retraction – technical material possible - better printing quality

Inconvenient : Low speed - The head is heavy – possible presence of ghosting – lower heating chamber



https://filament2print.com/fr/blog/94_extrusion-directe-bowden.html

Fused Filament Fabrication (FFF)

Advantages :

- Production of complex 3D parts from CAD file (Support available)
- "Easily" recyclable raw material
- Possibility of manufacturing several parts on the same plate
- Assembly reduction / Topological optimization / etc.
- Low costs
- Possibility of mounting the extruder on a robotic arm
- Possibility to have metal or carbon charged filament
- Resistance of the parts / material properties

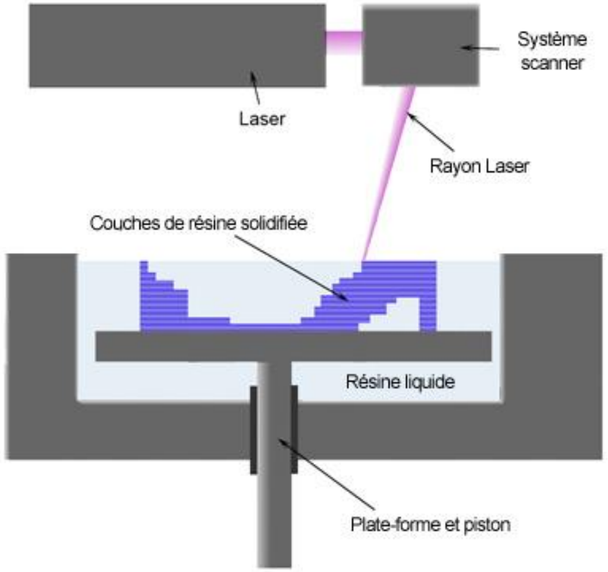
Disadvantages :

- Material anisotropy
- Removal of supports
- Limited size (typically <250 x 250 x 250mm)
- Small series
- Poor surface condition
- Poor surface condition / Low precision (+/-0.1mm) – layer 0,1 – 0,3mm – « Stairs » effect
- Slow manufacturing time

Stereolithography (SLA)

Technology:

Stereolithography is an AM process using a liquid pan of "resin" photopolymers that harden on contact with an ultraviolet laser. The 3D printed model is built layer by layer, which are deposited on a mobile platform. The laser hits the liquid tank solidifying the parts necessary for the realization of the digital 3D model.



Functioning:

- The plate is at maximum height, leaving a resin thickness equal to the thickness of one layer (between 0.05 and 0.15mm).
- The laser light-cures the resin
- The plate goes down (thickness of a layer)
- Etc.
- Cleaning the parts with chemicals products
- Baking in an ultraviolet oven to complete the hardening of the part

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Stereolithography (SLA)

Stereolithography (SLA)

Advantages :

- Complex part / support possible
- Among the most precise plastic technology (layers : 0,02 – 0,15mm) – Details : 0,1mm
- Quality of surface condition
- Several parts on the same plate
- Assembly reduction / Topological optimization / etc.
- Different types of resins including bio-compatible and food-grade materials (True Silicone for example)

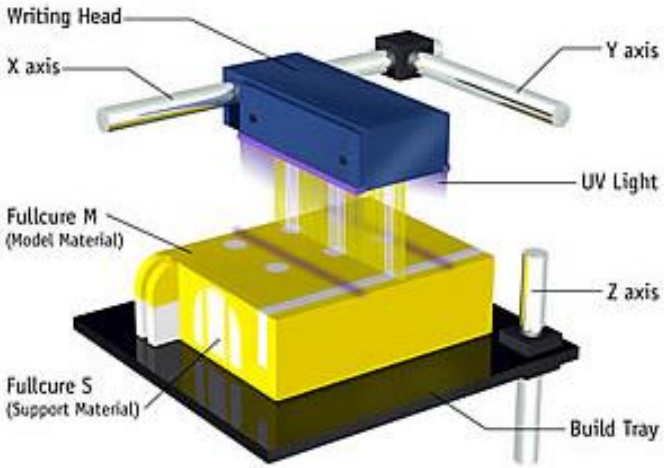
Disadvantages :

- Removal of supports
- Limited size (typically <250 x 250 x 250)
- Small series
- Resins only
- Handling chemicals for cleaning
- Passage in the oven after manufacture
- The resin must be hardened to be discarded as rubbish, otherwise: hazardous waste
- Fragility of certain elements
- Sensitive to sunlight and heat
- Few colors available / limited choice of materials
- More expensive than FDM and MJF

PolyJet

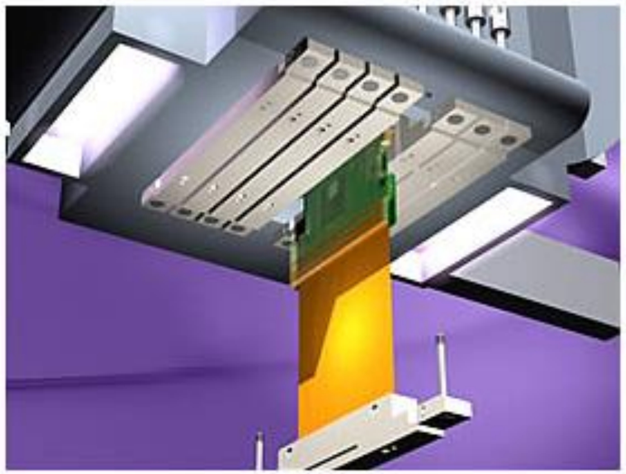
Technology :

PolyJet technology involves projecting photopolymer materials in ultra-thin layers onto a construction platform. Each photopolymer layer is immediately cured by UV light after spraying onto the part, resulting in a completely finalized model that can be used immediately without post-curing.



Functioning:

- The plate is at maximum height, leaving a distance equal to the thickness of a layer (between 0.05 and 0.15mm).
- The printheads (which each have several dozen tips) project microdroplets of material onto a substrate
- With each projection, hardening of the material by UV light
- The plate goes down (thickness of a layer)
- Etc.
- Cleaning the part with water



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PolyJet

PolyJet

Advantages:

- Excellent resolution (up to 0.016mm)
- Production of complex 3D parts from a CAD file (Support available)
- Among the most precise plastic technology
- Possibility of manufacturing several parts on the same plate
- Assembly reduction / Topological optimization / etc.
- Multi-materials, multi-colors possible

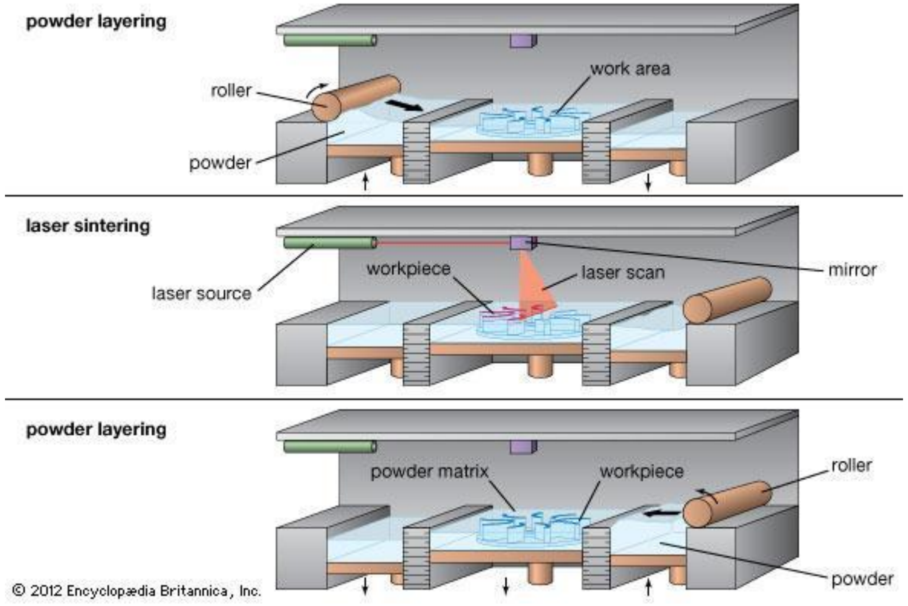
Disadvantages:

- Removal of supports
- Limited size (generally <250 x 250 x 250mm)
- Small series
- Plastic only
- Possible reactions of certain materials to light or heat
- Cost of the machine

Selective Laser Sintering (SLS)

Technology:

SLS 3D printing is done layer by layer from sintered or fused powders using energy produced by a high-power laser, such as a CO2 laser.



Functioning:

- Construction chamber with a movable platform and temperature maintenance to avoid deformation
- 2 pistons on each side provide the powder
- The plate is in the high position
- The scraper distributes a layer of powder on the plate
- The laser melts the layer
- The plate goes down
- Etc.

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Selective Laser Sintering (SLS)

Selective Laser Sintering (SLS)

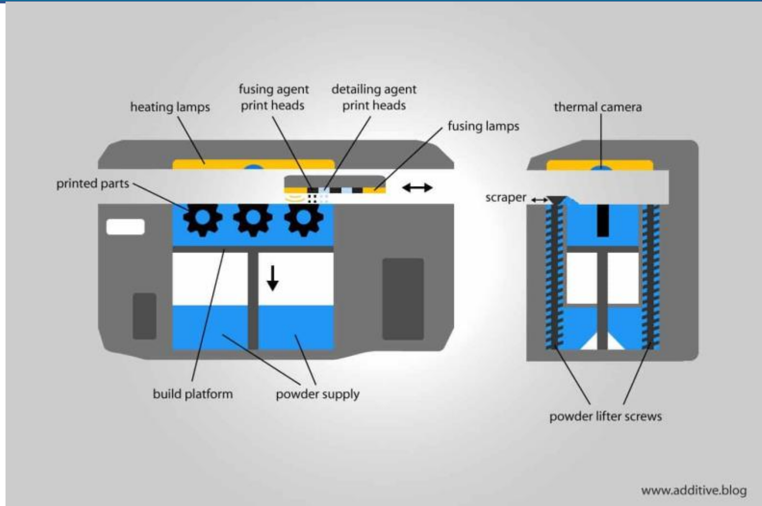
Advantages:

- Production of complex 3D parts (Supports possible)
- Possibility of manufacturing several parts on the same plate
- Assembly Reduction / Topological Optimization / etc.
- Accuracy (layers: 0.06 – 0.15mm) – Details: 0.3mm
- Fast manufacturing time

Disadvantages:

- Material anisotropy
- Removal of support
- Limited size (generally < 250 x 250 x 250mm)
- Small series
- Grainy Finish (Slightly Rough Surface)
- Single material

Multi Jet Fusion (MJF)



Technology :

Additive manufacturing by spraying binders (binding agent + detailing agent) on a powder bed introduced on the market by HP in 2016.

Functioning :

- Plate in upper position
- Distribution of a layer of powder
- Binder spraying
- Application of a liquid « detailing » agent to smooth the surface
- Heating to make the binder react (infrared)
- Cooling
- Post-processing station

- Material choice : PA12 (robust and functional parts), PA12 charged with glass beads (high rigidity), PA11 (ductiles parts), TPU 90A-01 ULTRASINT (Elastic parts)

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Multi Jet Fusion (MJF)

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Multi Jet Fusion (MJF)

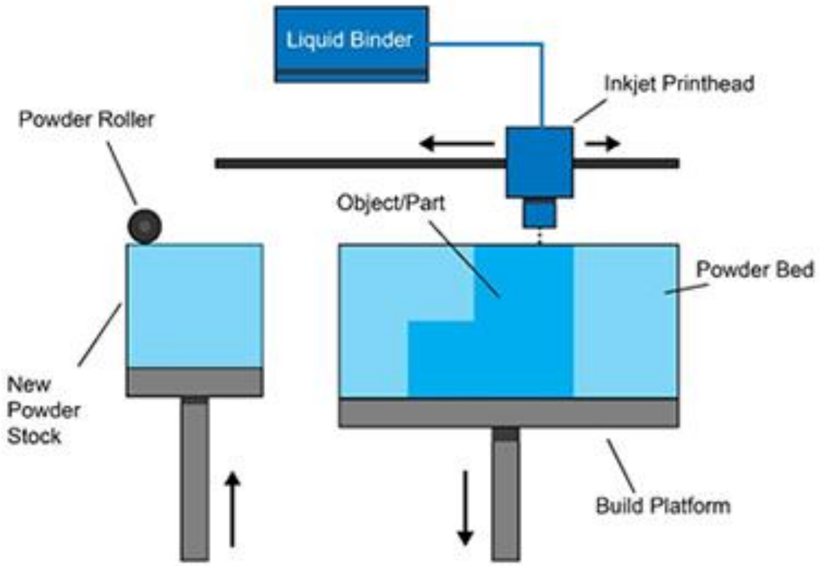
Advantages :

- Production of complex 3D parts
- Several pieces on the same tray and in the chamber
- Assembly Reduction / Topological Optimization / etc.
- 80 microns layers & 0.5mm details
- More isotropic mechanical properties compared to other processes
- Greater tensile strength than in SLS

Disadvantages :

- Poor choice of materials
- Limited dimensions: 284 x 380 x 380mm
- Necessary post-processing
- Long cooling time (24h)
- High costs

Binder Jetting (Plastic)



Technology:

Binder Jetting is an additive manufacturing method using a binder, locally deposited on a thin layer of powder, layer by layer.
Between each layer, the powder is heated in order to solidify it.

Functioning:

- Manufacturing chamber with mobile platform and powder heater
- 2 pistons on each side provide the powder
- The plate is in the high position
- The scraper (roller) distributes a layer of powder on the plate
- Deposition of the binder
- The plate goes down
- Etc.
- Powder removal + brushing
- Passage in the oven for sintering

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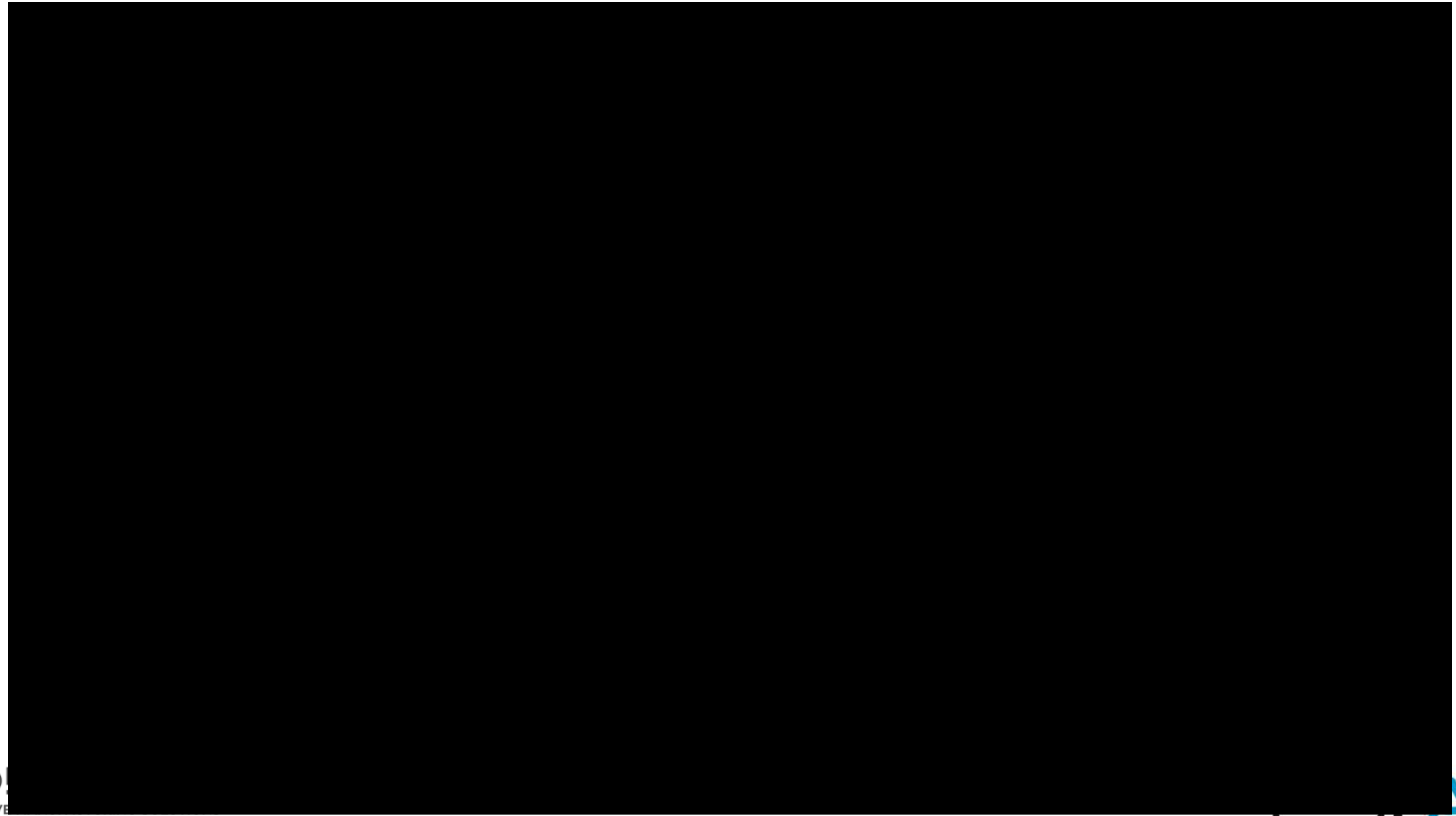
Binder Jetting (Plastic)



Binder Jetting (Plastic)

Advantages :

- Production of complex 3D parts from a CAD file (Support available)
- Possibility of manufacturing several parts on the same plate
- Assembly reduction / Topological optimization / etc.
- Relatively fast to manufacture
- Compatible with metallic powder, sand and ceramic

Disadvantages :

- Material anisotropy
- Removal of support
- Limited size (generally < 250 x 250 x 250mm)
- Depowdering required
- Baking (shrinkage during sintering)
- Machine cost
- Fragility
- Rough surfaces

ColorJet

Technology :

Binder jetting is an additive manufacturing method using a binder agent and color ink deposited locally on a thin layer of powder, layer by layer.

Functioning :

- Build chamber with movable platform and powder heater
- 2 pistons on each side supply the powder
- The tray is in the upper position
- The scraper (roller) distributes a layer of powder on the plate
- Deposition/projection of the binder with pigments
- The plate goes down
- Etc.
- Dusting + brushing
- Glue bath for hardening

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ColorJet

ColorJet

Advantages :

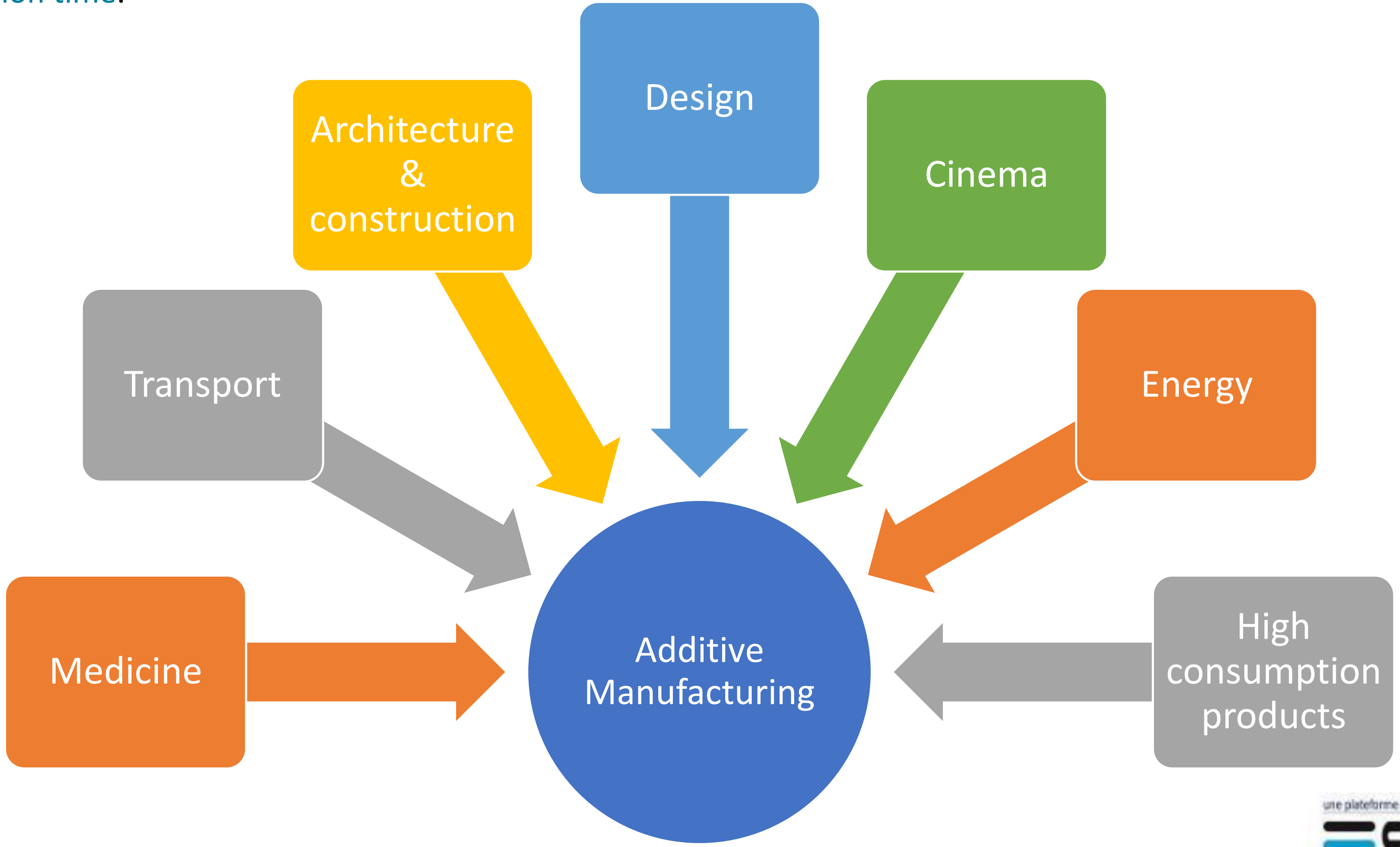
- Production of complex 3D parts (Supports possible)
- Possibility of manufacturing several parts on the same plate
- Assembly Reduction / Topological Optimization / etc.
- Quick Manufacturing
- Multi-color build quality
- Widely used in the sector of architecture, design, etc..

Disadvantages :

- Very fragile
- Removal of supports
- Limited size (generally < 250 x 250 x 250mm)
- Depowdering required
- Highly chemical and non-ecological glue bath
- Machine cost
- Rough surfaces

Chapter 3: Applications per sector

Today, 3D printing is capable of revolutionizing various sectors of the industry. While its primary function was to accelerate rapid prototyping, additive manufacturing has developed over the years, bringing real benefits to different sectors, whether in terms of materials used, costs or production time.



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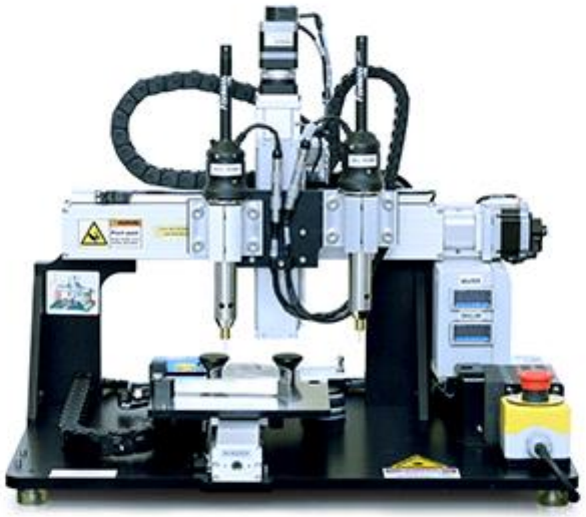
Medicine: Generalities

- Also called « Bio-Printing » or « Bio Manufacturing »
- The first laboratory with « bio 3D printing machine » commercialized is Organovo (NovoGEN MMX) in 2010
- In France, we can cite Poietis, who recently developed the most sophisticated bio-printer in the world for printing human tissues.

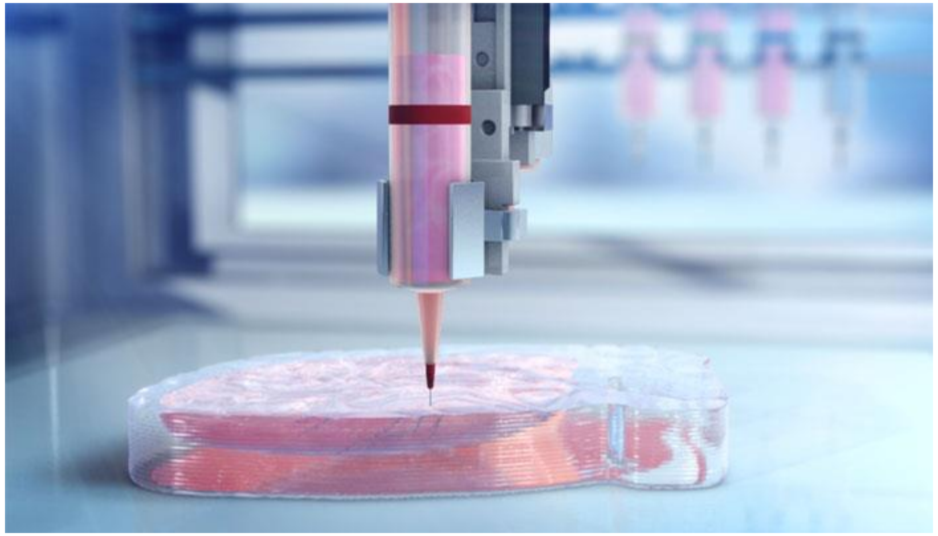


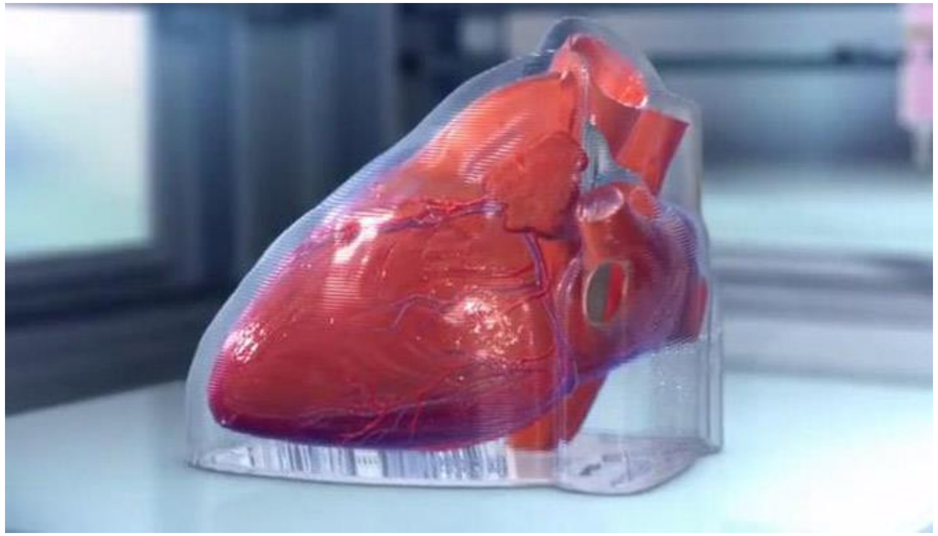
Ref.: https://www.invetechgroup.com/case-studies/organovo-novogen-mmx-bioprinter/

Ref.: https://www.a3dm-magazine.fr/news/medical/bio-impression-4d-poietis

Medicine: **Application 1 – BIOLIFE 4D**

- Bio printing of viable human heart for transplant
- 3D printing, layer by layer of living human cells taken from the patient and based on a 3D model to design the heart from the bottom up.
- Instead of fusing the layers together with a heat source or by light-curing (using a UV laser would kill the cells in the process), the deposition is done on a support scaffold to hold the cells in their place and then rest time to let the natural process of biological assembly take place (same process that occurs naturally in the body)





https://www.3dnatives.com/startup3d-biolife4d-15102018/#!

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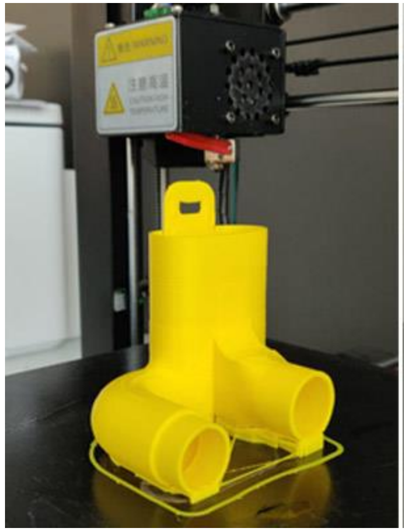
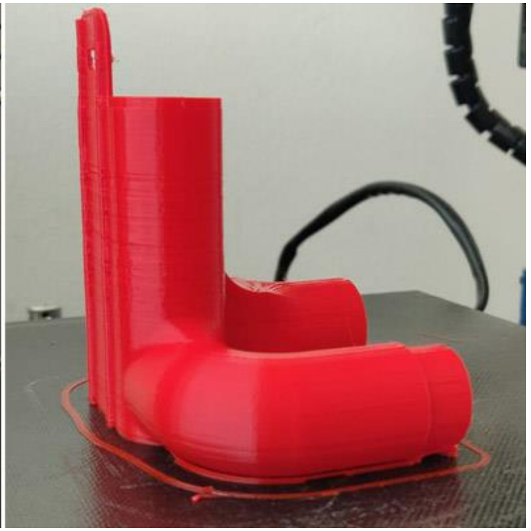
Medicine: **Application 2 – DECATHLON**

- More than 500 Decathlon masks transformed into respirators thanks to 3D printing
- Originally designed for snorkeling, doctors have added 3D printed valve transform them into emergency respirators
- FFF technology (extrusion of polymer filament)

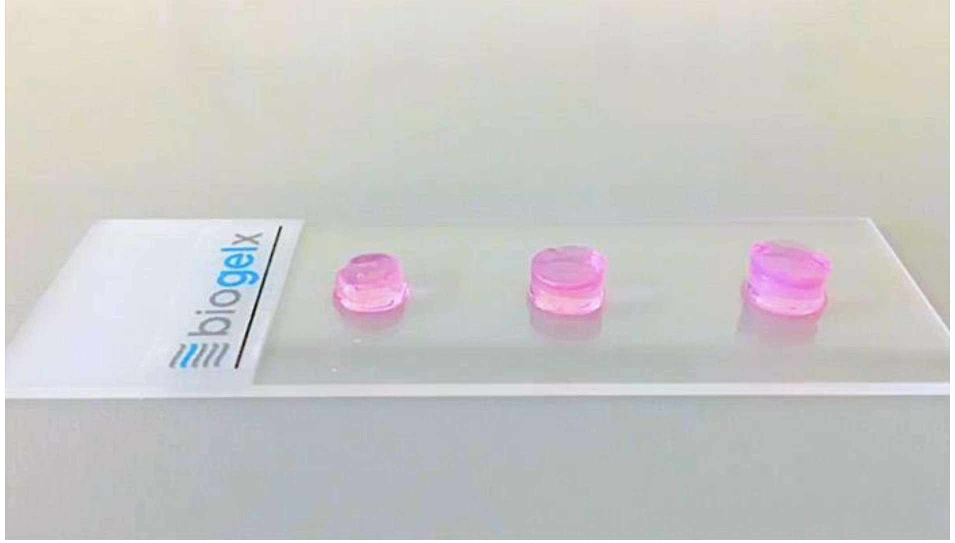




https://www.3dnatives.com/masque-decathlon-respirateur-3d-250320203/

Medicine: **Application 3 – BIOGELX**

- Spin-off from Strathclyde University in Glasgow
- Development and production of synthetic bio-inks for 3D cell cultures and bioprinting applications
- Drug development to improve testing processes and reduce costs (Synthetic peptide hydrogels for 3D cell culture applications)
- Biogelx ™ -INK were originally developed for use with extrusion-based technologies, representing over 80% of the current bioprinting market.



https://www.3dnatives.com/biogelx-bio-impression-120620193/

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Medicine: **Application 4 – BioMimics by Stratasys**

- Stratasys has just launched BioMimics, a platform that allows its users to print multi-material medical models to prepare for surgical operations, serve as supports for medical training and conduct various clinical tests.
- Very realistic model's 3D printed with several materials, which imitate both the soft tissues and the hard bones of the human body.
- Tools printed in one go, multiple materials, thus offering almost real conditions where it is possible to realize the materiality and consistency of a particular part of the body
- PolyJet printing technology that combines Inkjet and the use of photopolymers

https://www.3dnatives.com/biomimics-stratasys-30112017/

Medicine: **Application 5 – Chabloz Orthopédie**

- Manufacturing of orthopedic devices, from prostheses to orthotics, helmets to treat cases of plagiocephaly in newborns.
- Printer: HP Multi Jet Fusion (Polyamide powder – 80 microns layer – Powder melting system depositing droplets of a melting agent on a bed of PA12 powder)
- "Gains in patient comfort in terms of weight and ventilation, but also a better working environment for workshop technicians and almost endless design possibilities. "

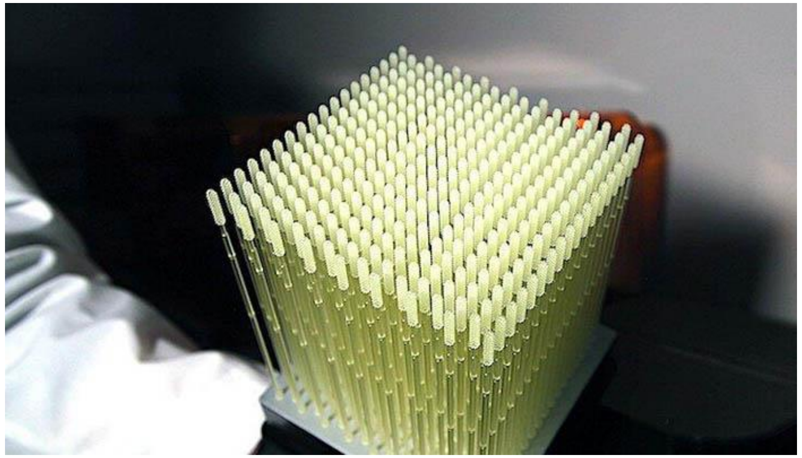
https://www.3dnatives.com/3D-compare/imprimante/jet-fusion-340
https://www.3dnatives.com/chabloz-orthopedie-hp-19122018/

Medicine: **Application 6 – Carbon & FormLabs: Swabs for COVID-19**

- Out of stock of Swabs for COVID-19: Additive Manufacturing can fix this broken supply chain by providing emergency solutions

- Provision of machines to fight Covid-19 by designing, validating and producing sample swabs. Carbon designers say they went through an intensive process, testing various 3D printed lattice structures on seven different models in 72 hours

- Formlabs has dedicated 250 SLA machines to this operation allowing it to create 150,000 nasal swabs per day, printed in one piece using biocompatible and autoclavable materials



https://www.3dnatives.com/ecouvillons-imprimes-en-3d-010420203/

Medicine: **Application 7 – Biomodex**

- Creation of organs and simulation models through 3D printing to allow surgeons to better perform their operations.
- From the medical imaging of patients, the startup is now able to manufacture the organ in 3D and thus improve the training of surgeons who can train on this more than realistic model.
- Biomodex is now specialized in ENT and orthopedics but is developing its solutions in the vascular and cardiovascular sectors with the help of recognized surgeons

https://www.3dnatives.com/biomodex-francais-innovant-140620173/

Transport: **Application 1 – DAB MOTORS - ALTER**

- Dab Motors is a French design workshop based in Biarritz that specializes in customizing motorcycles.
- Partnership between Yamaha and PolyShape to design ALTER (XSR 900 base)
- Several parts manufactured with Metal Additive Manufacturing which offers more lightness and solidity :
  - The rear frame loop (Aluminium with reticular structure that allows light to pass through from the rear headlight)
  - License plate support and headlight support
  - Upper triple clamp (54% weight gain)
  - Etc.
- Many advantages, particularly in terms of production times and costs.

https://www.3dnatives.com/alter-moto-impression-3d-050720183/#!

Transport: **Application 2 – JAMADE Germany - AMAZEA**

- AMAZEA is an underwater scooter in which 75% of the parts have been printed in 3D
- Designed on a BigRep large format 3D printer, the device would allow you to explore the marine ecosystem
- The body and front parts of the jet ski were produced on three BigRep ONE large format 3D printers
- Material (Pro HT) was developed by BigRep, it is a material derived from organic compounds, biodegradable under the right conditions and therefore more respectful of the environment compared to other thermoplastics on the market
- "We opted for the BigRep ONE because of its cost effectiveness, precision and quality compared to the extremely high investment that traditional tools represent"
- AMAZEA is perfectly waterproof: by manufacturing it all at once, the company is freed from the constraints of assembly and therefore the risk of leakage.

https://www.3dnatives.com/amazea-scooter-impression-3d-30012020/#!

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Transport: **Application 3 – APWorks (subsidiary of Airbus) & Dassault**

- At the Paris Air Show, the Airbus subsidiary specializing in 3D metal printing, Airbus APWorks GmbH, announced the signing of a partnership with Dassault Systèmes.

- This new collaboration should help the aeronautics and defense industries to make greater use of this technology in series production.

- The aerospace sector is disrupted by additive manufacturing, which allows the creation of more complex but lighter parts, at unbeatable costs. By partnering with additive manufacturing experts, the aircraft designer can become more efficient and gain in efficiency.

- APWorks and Dassault Systèmes will therefore work together to develop a process that will make it possible to control all the parameters involved in the additive manufacturing of a part and therefore to better manage its value chain.

- The partnership is based in particular on the use of the 3DEXPERIENCE platform

https://www.3dnatives.com/apworks-et-dassault-systemes-270620173/#!

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Transport: **Application 4 – BMW – S1000RR**

- Integration of a 3D printed chassis with organic design but also a swingarm designed by 3D technologies. An initiative that would allow the German to create faster and more efficient parts, two key points in the automotive sector.
- The motorcycle thus joins the many vehicles that are equipped with 3D printed parts and have seen their performance improve.
- BMW announced last week the opening of a new center dedicated to additive manufacturing, representing an investment worth 10 million euros in order to integrate the technology into its production cycle
- Since investing in a Multi Jet Fusion 3D printer from HP in 2016, BMW has been reimagining its cars with 3D printed parts, such as its i8 Roadster model. They want to be more complex in their design but also lighter.
- BMW claims that "3D printed parts offer a high degree of freedom in terms of design and are quickly manufactured, always with a high level of quality. We don't need traditional manufacturing tools like casting moulds; everything is now digitized."

https://www.3dnatives.com/moto-bmw-25042018/#!

Transport: **Application 5 – GENESIS - Essentia Concept**

- Genesis is the brand of luxury vehicles from the manufacturer Hyundai, which recently made headlines with a new concept car, Essentia Concept.
- Hyundai joins the list of automakers using additive manufacturing to boost efficiency – whether creating futuristic concept cars or repairing old classic cars, 3D printing is an increasingly popular design method.
- Elements 3D printed, including a kind of mesh that would connect the interior and exterior surfaces.
- The automaker goes on to explain that it opted for a multi-material approach with different colors.

https://www.3dnatives.com/essentia-concept-030420183/#!

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Transport: **Application 6 – Ford – Wheel nuts**

- Ford designed 3D printed lug nuts to protect metal rims. These nuts are made using a unique biometric signature based on the driver's recorded voice, so they are fully personalized. The manufacturer even specifies that they are impossible to reproduce.

- A supporter of additive manufacturing for years, Ford continues to develop innovative products to provide a more enjoyable experience for all its drivers. Last year, he presented us with an air manifold 3D printed from aluminum to improve the performance of one of his vehicles – it became the largest automotive metal part ever created by additive manufacturing.

- A great example that shows how additive manufacturing takes personalization to another level and makes it possible to design innovations more quickly.

- Lars Bognar, Research Engineer, Advanced Materials and Processes, Ford of Europe concludes: “Having our own printer allows us to make tools and parts exactly when we need them, and replace them faster. For some tools, the delivery time could be up to eight weeks, but with 3D printing, the time has been reduced to just five days.”

https://www.3dnatives.com/ford-ecrous-imprimes-en-3d-290120203/#!

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Transport: **Application 7 – Boeing 777X – 300 printed parts**

- What is particularly interesting with this new aircraft from the American giant is that its two GE9X engines integrate more than 300 3D printed parts, produced by GE at Avio Aero in Cameri, Italy, and GE's additive technology center in West Chester, in Ohio.

- Several sizes of components would have been designed, whether temperature sensors, fuel mixers or even heat exchangers.

- The aircraft is said to produce 10% lower fuel emissions than the competition with integration of fuel nozzles printed in 3D metal which come to reduce fuel emissions and therefore lower costs.

- Ted Ingling, GE9X program manager, explains: “The Boeing 777X flight test program with the GE9X will validate the performance goals and benefits of this aircraft/engine combination. The GE9X is the most fuel efficient jet engine GE has ever produced. We have found additive manufacturing to be very powerful, especially in the early stages of development, where it allows the design team to iterate on concepts much faster. »

https://www.3dnatives.com/boeing-777x-fabrication-additive-270120203/#!

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Construction: **Application 1 – Apis Cor**

- The city of Dubai has 3D printed the largest administrative building in the world on two floors. All the walls were built using the concrete 3D printer from Apis Cor

- The 640 square meter structure now meets the standards of the city, which aims to 3D print 25% of its buildings by 2030.

- “This project is a major turning point in the construction sector. 3D printing technologies will increase the speed of execution and lead to the completion of buildings in record time.”

- The building structure was 3D printed directly on site, without additional assembly steps. The 3D printing process was done under natural weather conditions. The main objective was to carry out extensive research and development work to test the equipment in extreme climatic conditions, here heat and humidity.

- According to the Dubai Municipality, the process used less labor (only 15 workers) and generated around 60% less waste. The building would incorporate a number of features, such as internal wall structures to increase insulation efficiency. The walls are made up of hollow spaces to improve thermal insulation and ultimately reduce energy consumption.

https://www.3dnatives.com/batiment-imprime-en-3d-apis-cor-29102019/

Construction: **Application 2 – Apis Cor (2)**

- In Moscow, Apis Cor, the Russian manufacturer of concrete 3D printers, 3D printed an entire house in just 24 hours in extremely cold temperatures. An initiative that shows how 3D printing can revolutionize the construction sector.

- Apis Cor manufactures 3D printers specifically designed to build large concrete structures. The machines are mobile and can be installed on site in 30 minutes. Its removable arm can cover an area of 132m2: 3D printing is then done easily and quickly.

- What differentiates Apis Cor machines from others is their ability to manufacture the interior and exterior of the structure and not just the foundations. The printer's removable arm ensures more flexibility to move around the structure, with an extruder that pivots on two levels for better speed.

https://www.3dnatives.com/maison-impression-3d-02032017/#!

Construction: **Application 3 – Dassault Systèmes & XtreeE**

- In partnership with Dassault Systèmes, the French startup XtreeE presented a structure with an organic design printed in 3D.
- The architecture of the pavilion is based on biomimicry, taking strong inspiration from nature by taking up the appearance of a coffee bean for the structure and walls echoing the forest
- The material used is an experimental cement developed by LafargeHolcim. It is a cement specially designed to be 6 to 8 times stronger than conventional cement. In particular, it is reinforced with metal fibers, which makes it more resistant to possible deformations and better withstands external pressures such as pollution and bad weather.
- The printing, meanwhile, was carried out with a multi-axis industrial robot from the Swiss ABB and called IRB8700. The use of new technologies in 3D printing also made it possible to print the roof, an integrated bench, and the walls in a single operation.
- This innovation thus opens the way to new applications in the field of architecture with multiple advantages: lower costs, more complex shapes, accelerated manufacturing speed but also a lower carbon footprint.

https://www.3dnatives.com/pavillon-impression-3d-23092016/#!

Construction: **Application 4 – New Story & ICON**

- The Texas capital, Austin, is now home to its first 3D printed house, created specifically to show how concrete 3D printing could help developing countries. A project led by New Story, an association that comes to the aid of underprivileged areas and ICON, a startup specializing in 3D concrete printing that wants to build more efficient and sustainable custom buildings. Together, they want to build 3D printed houses to provide the 1.2 billion people in need with an adequate housing solution.

- “Conventional construction methods have many drawbacks and problems that we have taken for granted for so long that we have forgotten that an alternative could exist,” explains Jason Ballard, co-founder of ICON. “With 3D printing, you not only have a continuous thermal envelope, high thermal mass, and near-zero waste, but also higher speed, a much wider design palette, and of optimum resilience. It's not 10% better, it's 10 times better.“

- ICON also claims that a house of this size would cost around $4,000, a relatively low price compared to other solutions on the market.

https://www.3dnatives.com/maisons-imprimees-en-3d-13032018/#!

Construction: **Application 5 – Yhnova project - Nantes**

- Additive manufacturing in the construction sector is booming, especially when it comes to creating more affordable housing. The New Story project is a perfect example: the association wants to create 3D printed houses for less than $4000 and thus offer cheaper solutions to fight the housing crisis. The French Yhnova project is part of a similar approach; the consortium of companies behind this initiative has 3D printed social housing that would be 30% cheaper and faster to build.

- The construction have lasted only a few months – between the idea of the project and its realization, it happened only 11 months. A very shortened duration which would be linked in particular to the process developed by the University of Nantes, BatiPrint3D.

- This uses a robotic arm that would extrude layers of different materials, two layers of expansive-type polyurethane foam and a third of concrete, in order to create a structure with a more or less complex shape.

- The researchers thus hope to show that the BatiPrint3D process can be an adequate solution on land where conventional construction work is not always easy to carry out.

https://www.3dnatives.com/logement-social-imprime-en-3d-270320183/#!

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Construction: **Application 6 – MX3D Bridge**

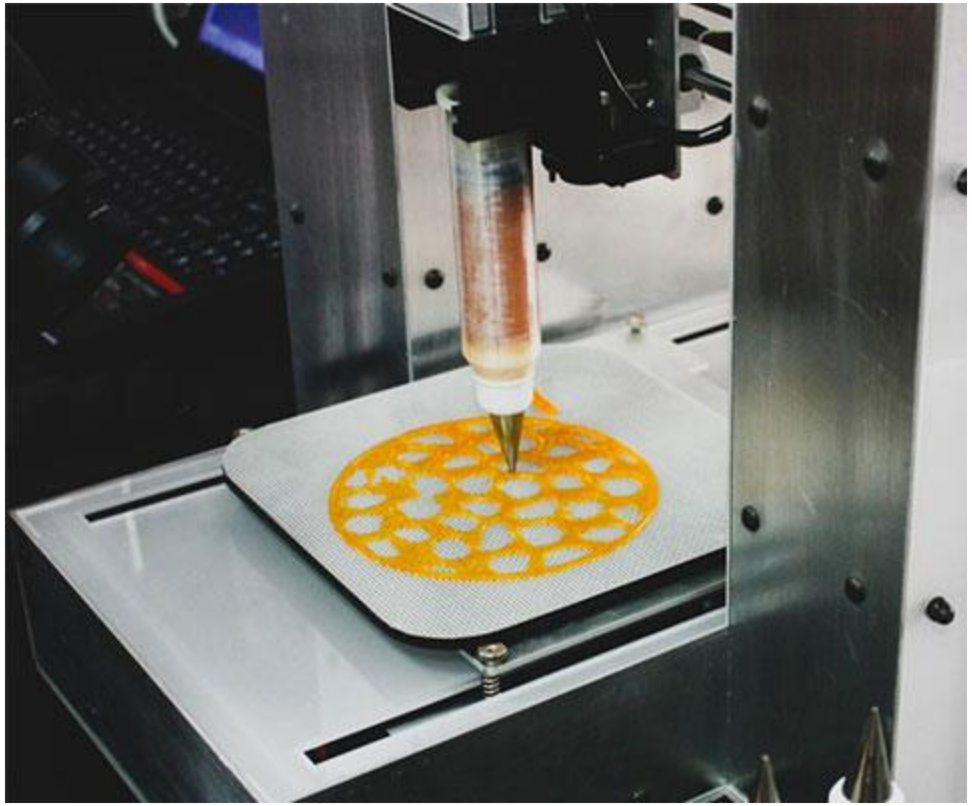
- MX3D 3D printed a 12-meter-long stainless-steel pedestrian bridge and is now placed and crossing one of the Amsterdam's canals in the old city center since 2021.
- Development of a smart sensor network to monitor the bridge's health in real time. A great example of data centric engineering.
- The structure, which is made of 4,500 kg of stainless steel, was 3D printed by robots in a factory over a period of six months before being installed above the canal.
- "This robotic technology finally makes it possible to 3D print larger optimized designs in metal. This results in significant weight reduction and reduced impact for parts manufactured in the tooling, oil, gas and construction industries. The technique can thus lead to more durable structures." said MX3D co-founder Gijs van der Velden.

https://www.3dnatives.com/pont-en-acier-imprime-en-3d-04042018/#!

Design / fashion :

Jewelry:

Food:



https://www.3dnatives.com/en-cas-imprimes-en-3d-250220193/

Textile:

https://www.3dnatives.com/imprimantes-3d-pret-porter-23072015/

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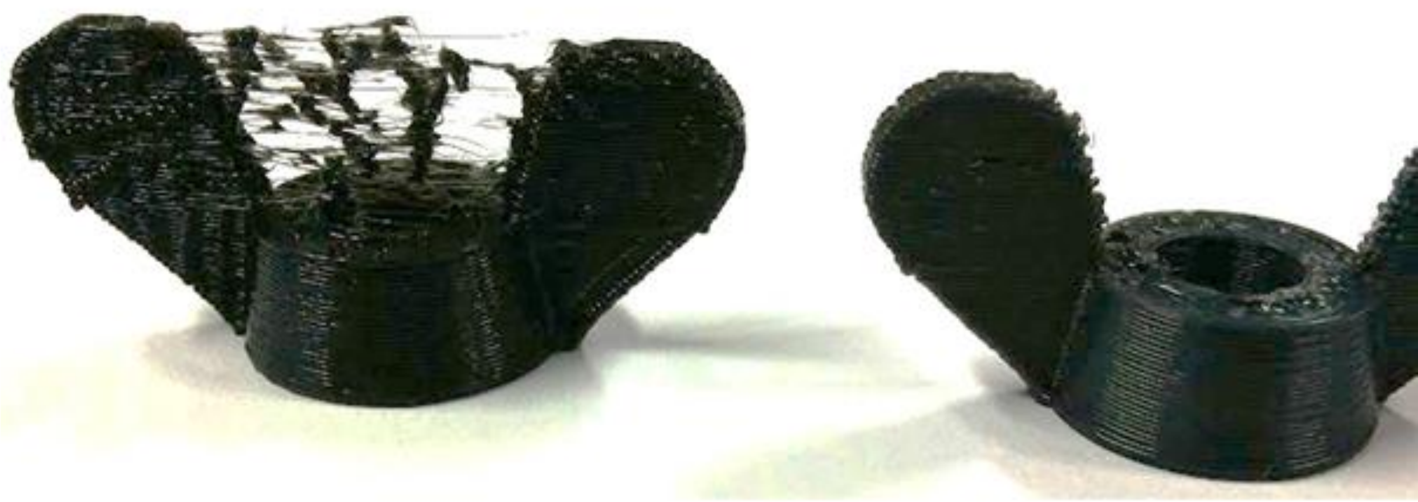
Oozing

Symptoms: Fine filaments are woven into the empty spaces between the different parts of the 3D printed part.

Possible causes: Plastic continues to flow from the head when moving it, due to the residual pressure in the heating body and the fluidity of the molten plastic.



Proposed fix:

- Increase the filament retraction length. The recoil of the filament will cause the pressure in the printhead heater to drop. The effect can be modulated by also adjusting the withdrawal speed directly in your slicer.

- Increase the printhead movement speed. This gives less time for the molten plastic to flow and thus leave traces between the printed parts.

- Lower the extrusion temperature of your plastic. If it is too high, the plastic is more fluid and therefore escapes more quickly through the extruder.

Overhang

Symptoms: Collapse or poor quality of an overhanging surface, it leaves like small beads.

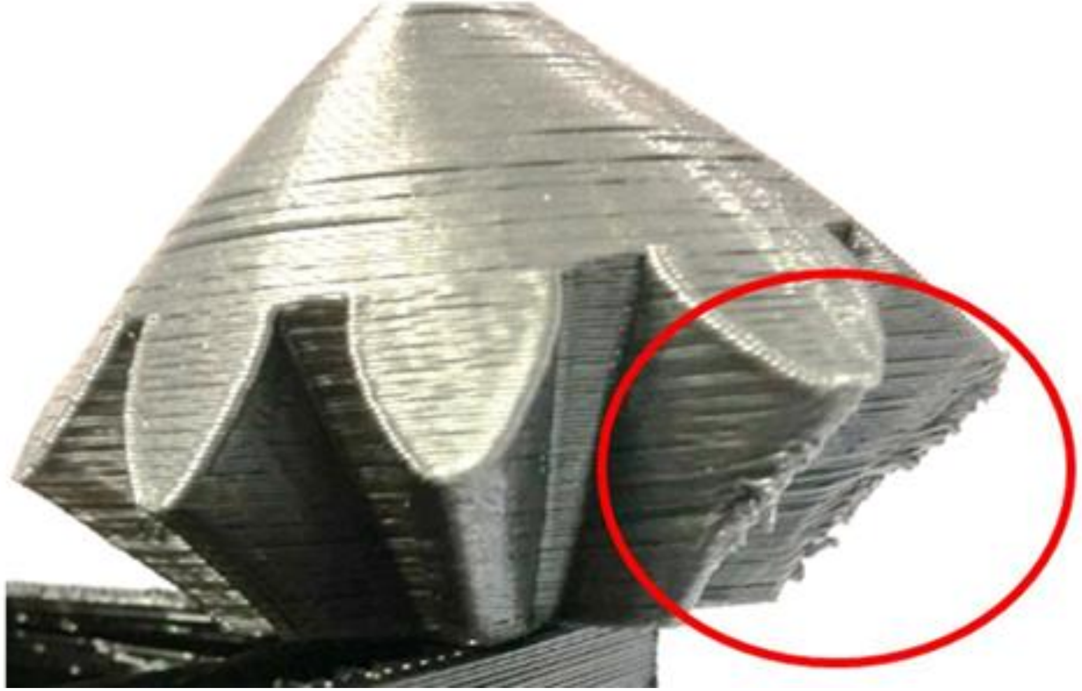
Possible causes: The solidification of the plastic deposited on the periphery of the overhang is not fast enough and the deposited filament therefore moves before it solidifies. The phenomenon is repeated or accentuated from one layer to another.

Proposed fix:

- Ventilate the deposited plastic more efficiently by adding a fan to your extruder, for example, or directly with a portable fan.

- Create print supports below overhangs.

- Change the orientation of the part to avoid overhangs.



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Delamination

Symptoms: The contours are not linked enough together.
Flat faces are not fully covered.

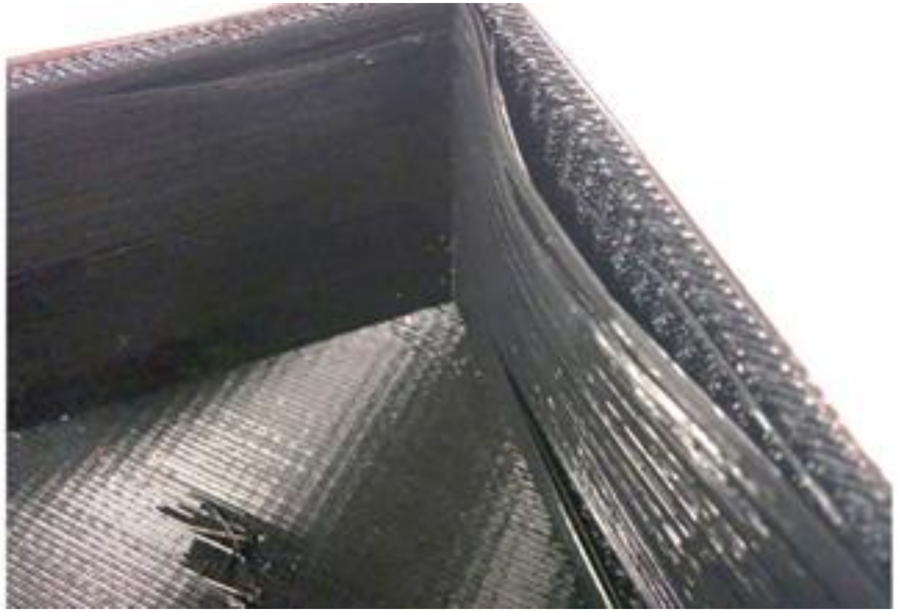
Possible causes: There is not enough deposited material. Too narrow, the deposited thread does not touch each other enough, and therefore does not stick to the neighboring thread.
Presence of impurity in the nozzle which hinders the passage of the molten material.
The extrusion temperature is too low the wire dries too quickly or shrinks and therefore does not stick to the neighboring wire.

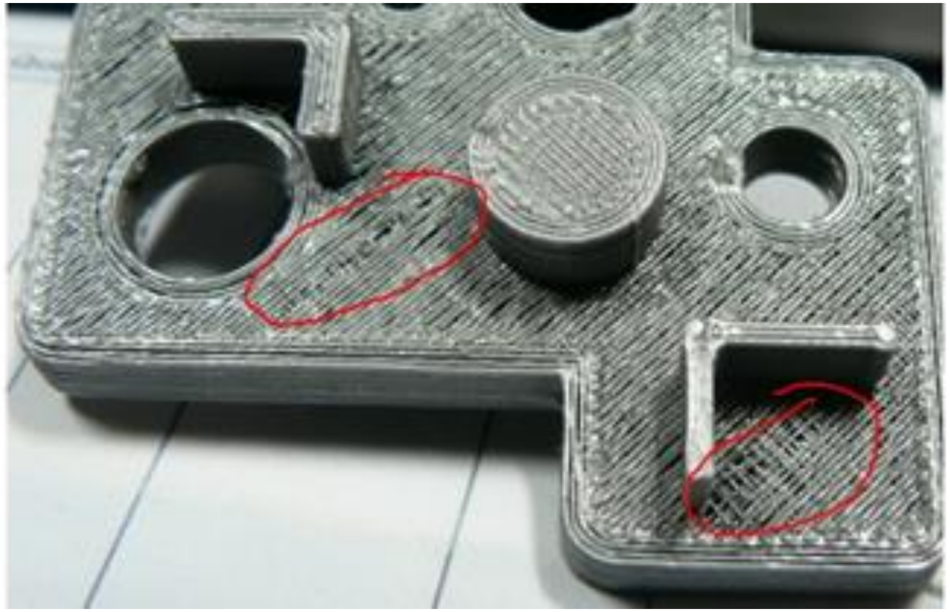
Proposed fix:
- Calibrate the extruder to have a material flow consistent with the slicer data.

- Unclog the extrusion nozzle.

- Increase the extrusion temperature.

- Increase the overlap rate in your slicer.





Lack of material on thin walls

Symptoms: The edges of a very thin section are not strong enough, there is not enough material.

Possible causes:
- Back-retract or recovery after retract not effective enough.
- Poor yarn solidification.
- Filament drive slipping during retracts.

Proposed fix:
- Decrease retraction speed and length when printing.
- Increase “extra length on retract”
- Increase the spring pressure on the extruder.

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Blisters

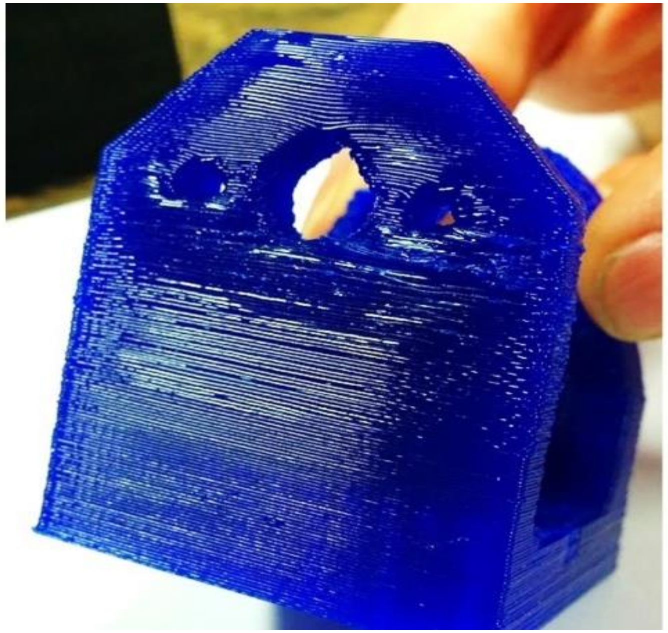
Symptoms: Blisters, nonconforming geometry such as small bumps that are seen mainly on areas that have a small surface area.

Possible causes:

- Filament too hot at the time of its extrusion or filament cooling system not efficient enough.

Proposed fix:

- Putting more pieces on the board at print time. The nozzle will therefore print more objects and therefore will give the part more time to cool before going over it again.
- Better cool your 3D printed object by adding cooling systems.



Delamination of thin walls

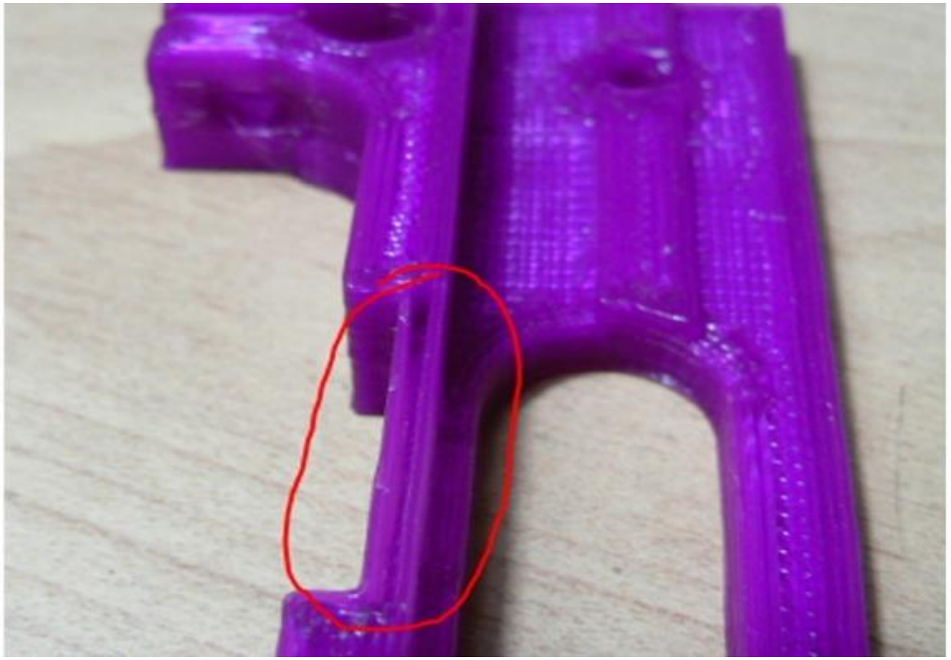
Symptoms: A thin wall and without filling, sees its wires separate, they are not glued together laterally.

Possible causes:

- The walls of your 3D print are too thin, or they are not suitable for this too small size..

Proposed fix:

- Draw thicker wall thicknesses to match the thickness of the filament.Impose in the slicer settings a sub-multiple deposit width of the wall width, while remaining compatible with the extrusion diameter and the layer height.
- Change slicer.



Horizontal offset

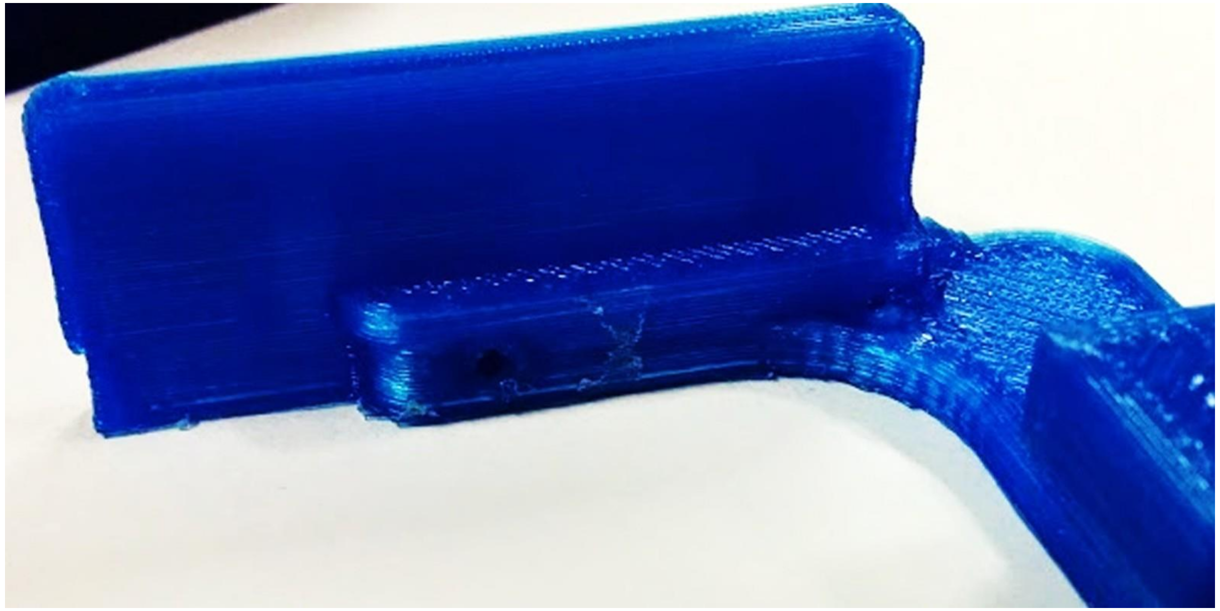
Symptoms: Offset of a layer along the X or Y axes (or both).

Possible causes:

- Problem moving printhead or plate.

Proposed fix:

- Decrease the acceleration on the axis concerned by the problem.



Irregular offset

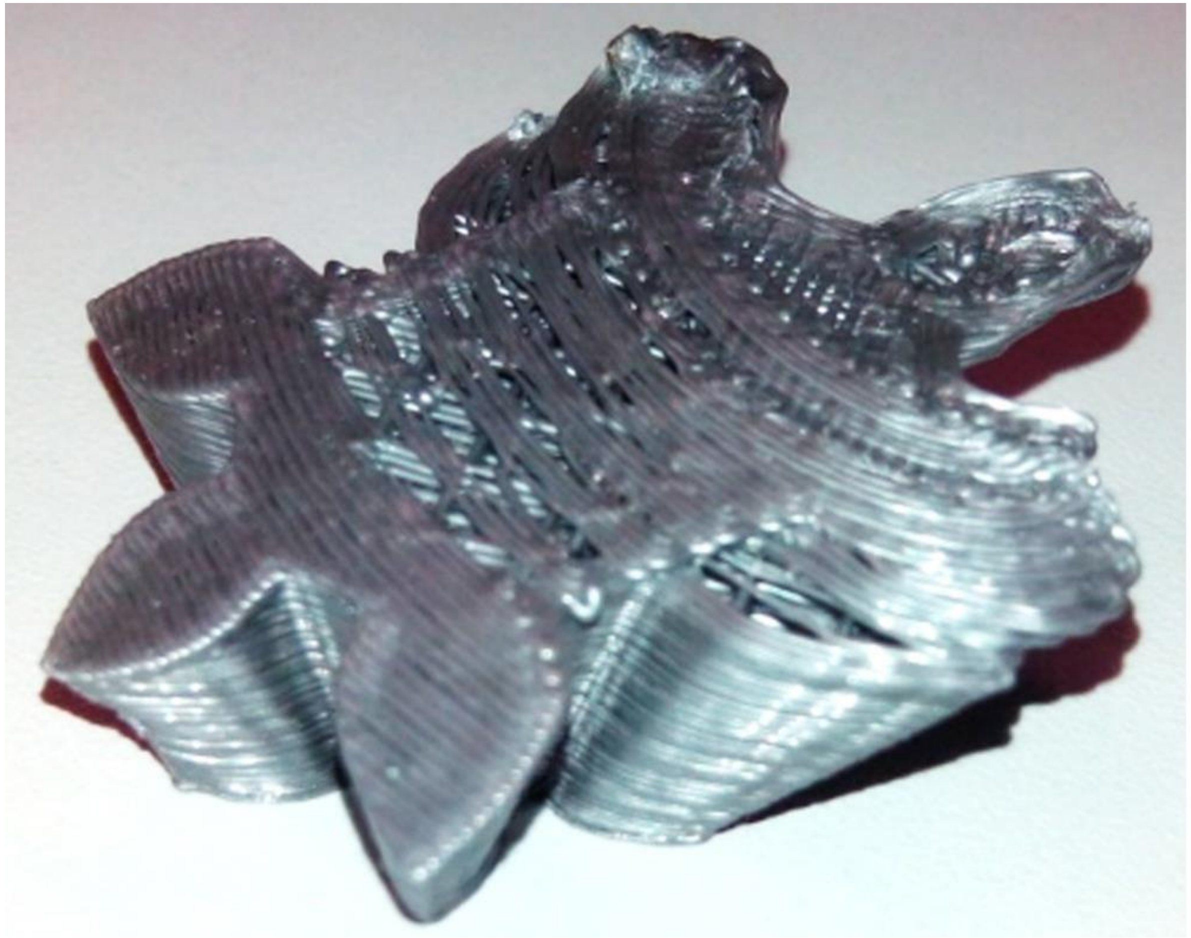
Symptoms: Almost systematic offset of the layers along the X and/or Y axes from a certain printing height.

Possible causes:

- Fault in movement of the head or the plate due to overheating of the motors which go into safety.

Proposed fix:

- Cool the motors via cooling systems (fans).



Curling

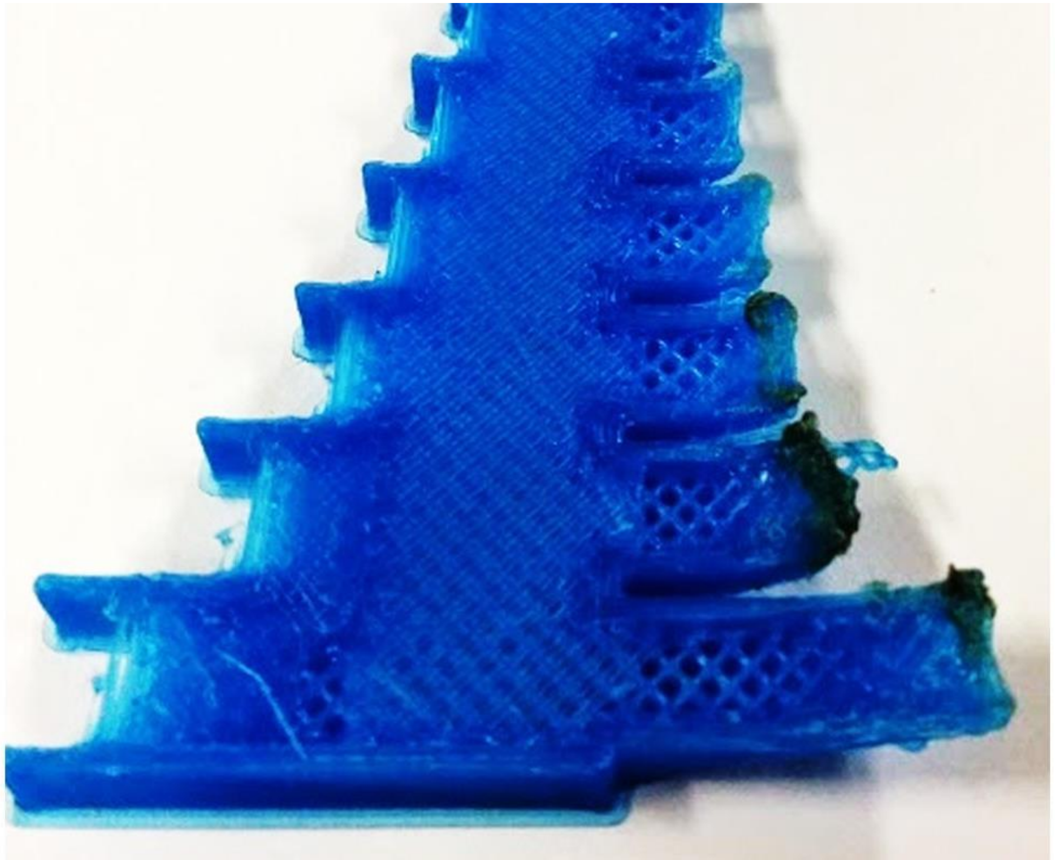
Symptoms: Deformation in the Z direction during 3D printing. This is increased in case of strong overhang.

Possible causes:

- Poor solidification, shrinkage effect due to the difference in temperature of the wire deposited on the previous cooled layer.

Proposed fix:

- Increase the slope at the 3D model of the part to reduce the overhang.
- Cool the deposited plastic further via a ventilation system.
- Add print support to relevant locations.
- Raise the temperature of the chamber to reduce residual stresses



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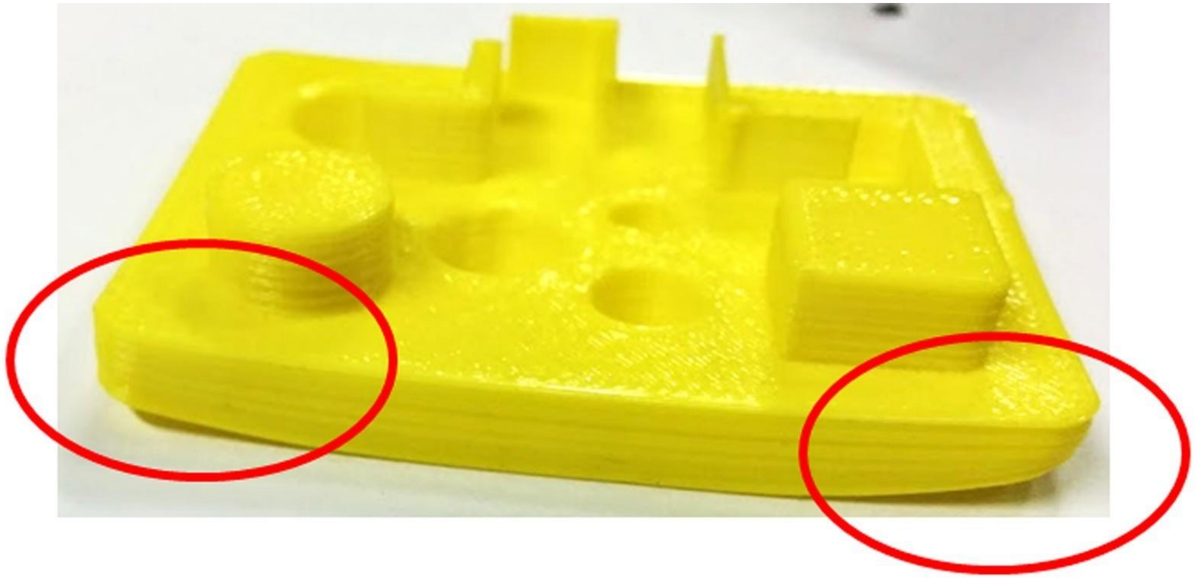
Warping

Symptoms: The corners of the printed object come off the plate generating an uneven base.

Possible causes:

- Poor adhesion of the part to the plate.
- Material shrinkage coefficient too high.
- First layer not flattened enough against the board.



Proposed fix:

- Change printing material because warping happens less with PLA.
- Put adhesive on the printing plate (glue, tape, lacquer...).
- Correctly adjust the height of the bed before printing.
- Apply a first thinner layer to further crush the deposited thread.
- Add a brim below the first layer.
- Heat the tray.
- Clean, degrease the support.
- Change the filling strategy.
- Decrease the interior fill density of your 3D printed object.
- Raise the temperature of the chamber to reduce residual stresses

Too low extrusion density

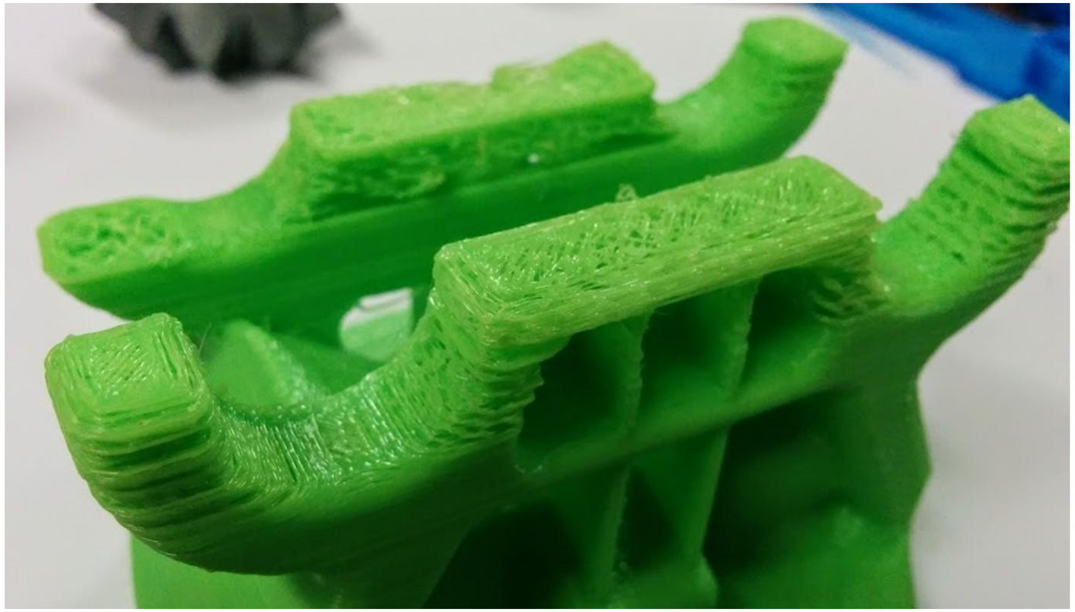
Symptoms: Density of material not conforming.

Possible causes:

- Material flow too low

Proposed fix:

- Unclog the extrusion nozzle.
- The filament is blocked upstream of the extruder (node in your spool for example)
- Review the wire drive (problem with the knurled screw for example)

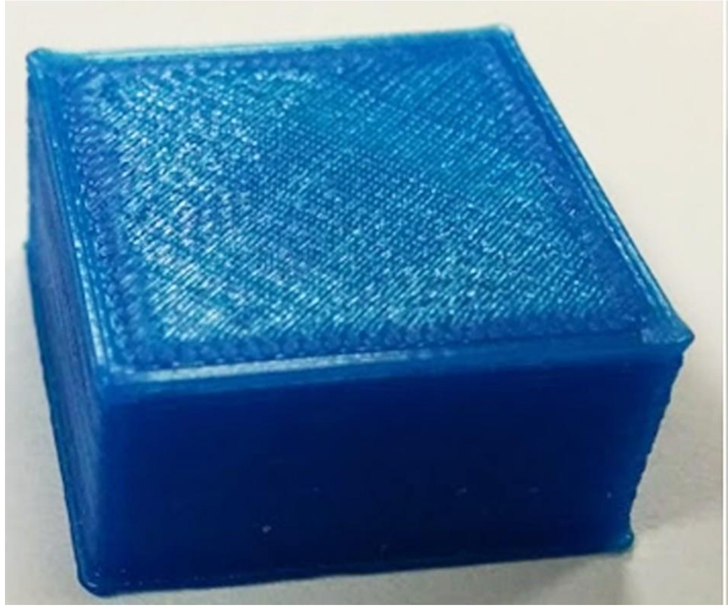


Round corners

Symptoms: The corners are not straight enough; they can even stick out and increase the size of the part.

Possible causes:
- Excess material deposited in the corner, due to too much slowing down of the nozzle during its passage through this location.

Proposed fix:
- Deliberately soften the angle of the part in 3D modeling software.
- Increase the "jerk" on the axis control of your 3D printer.



Black drops

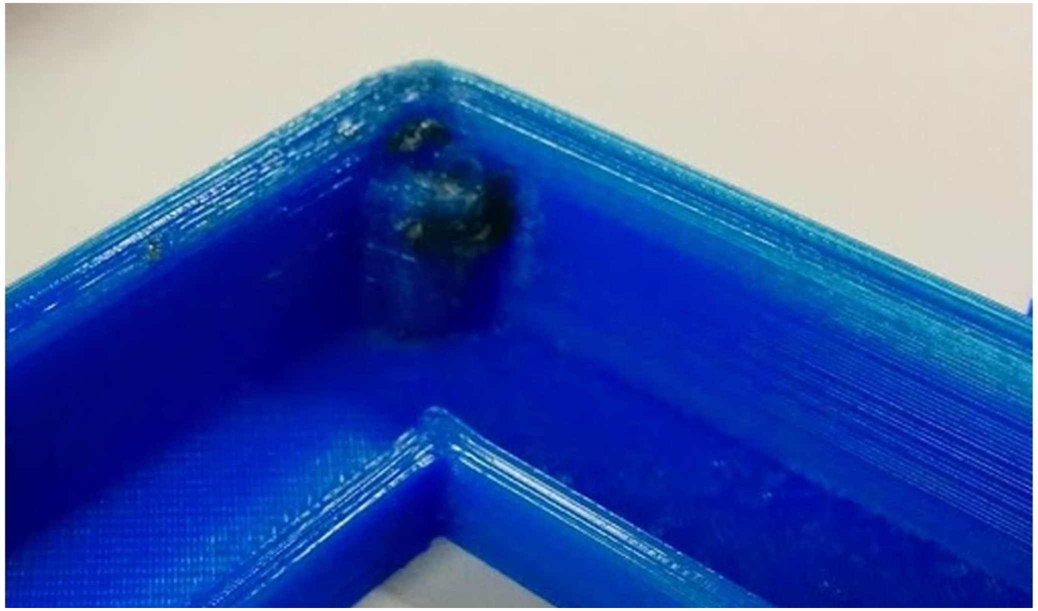
Symptoms: Presence of burnt (blackened) plastic on certain places of the printed object.

Possible causes:

- Poor nozzle sealing results in burnt polymer flowing around the nozzle.

Proposed fix:

- Remove the nozzle and redo its seal.



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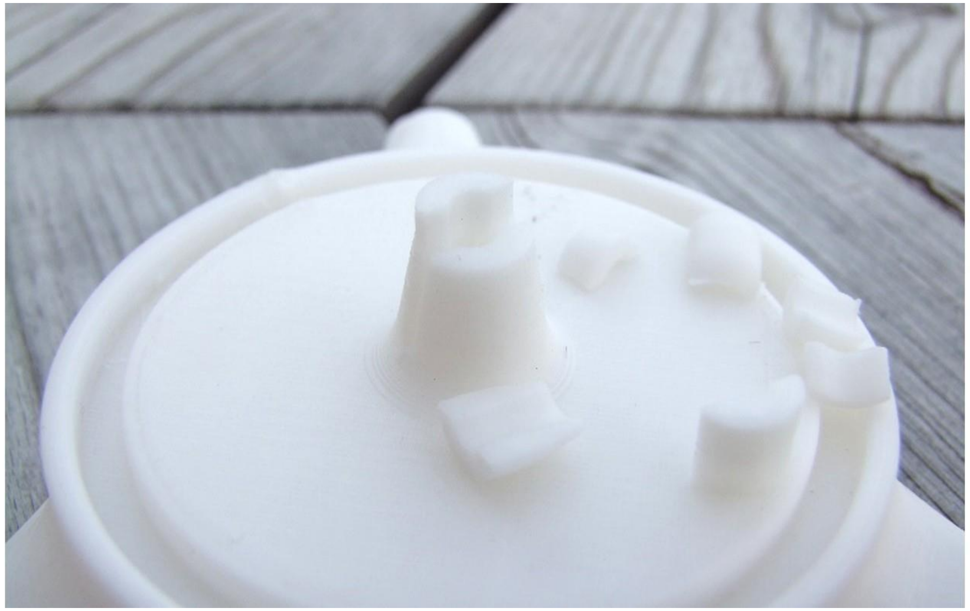
Bad welding / fragility

Symptoms: Breakable part at the level of the grip between two layers of printing.



Possible causes:

- Excessive cooling, the deposited layer does not adhere well to the previous layer because it is not hot enough when it is deposited.

Proposed fix:

- Decrease fan speed when printing.
- Increase the minimum printing speed in the slicer.

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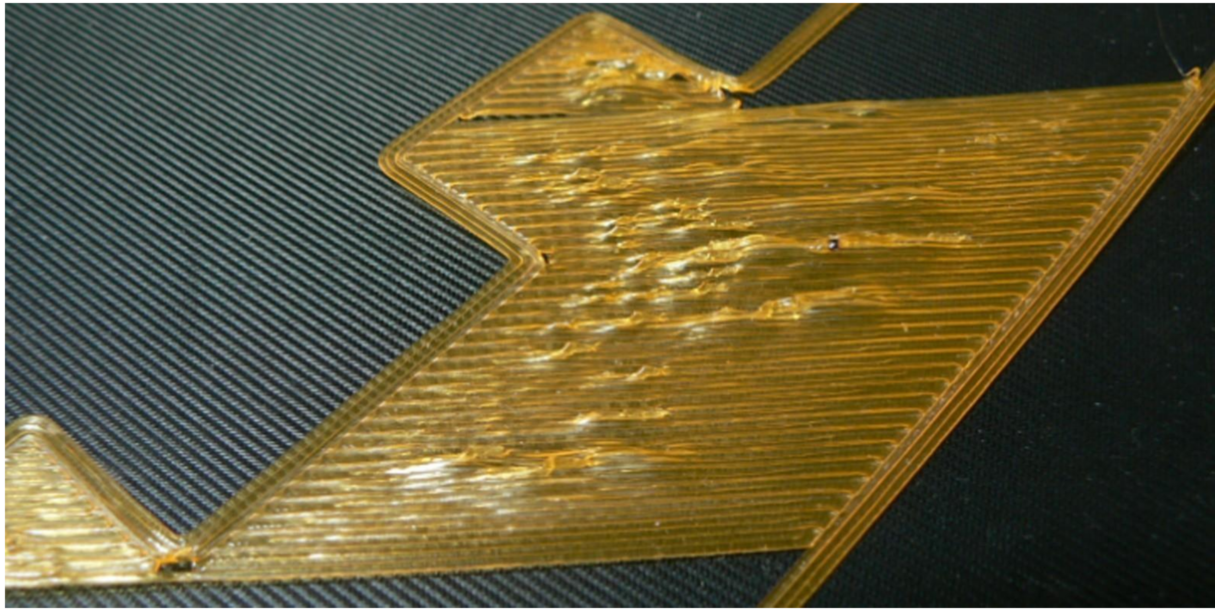
Bubbles on 1st layer

Symptoms: The first layer peels off locally from the plate in the form of bubbles.



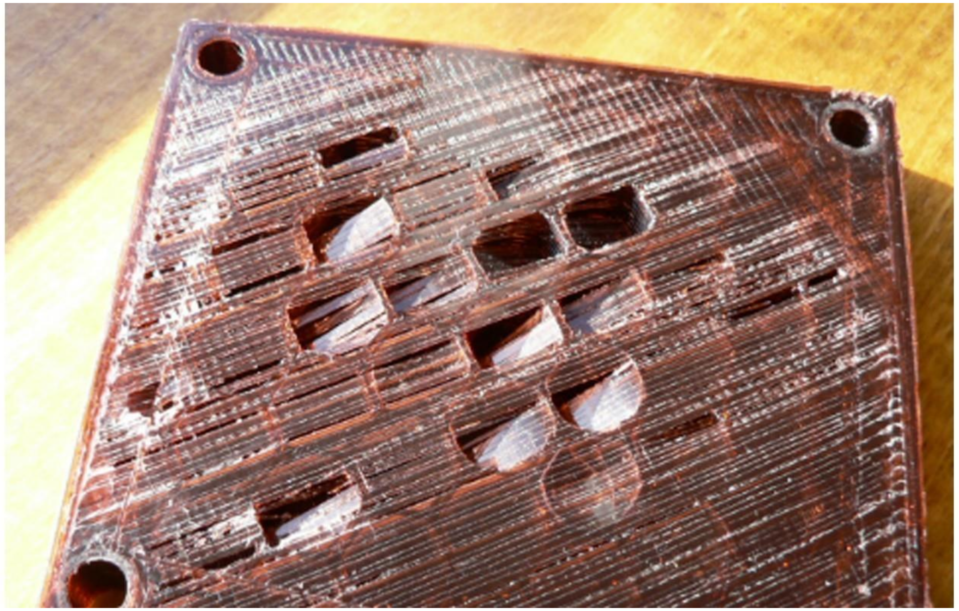
Possible causes:

- Presence in the material of humidity which gradually vaporizes on contact with the heating plate.
- Insufficient heating bed temperature for the material used.
- Nozzle too high – bad adjustment of the Z offset.
- Movement speed of the first layer too high.

Proposed fix:

- Store the coils of raw material in a dry place, in closed packaging, with the desiccant bag or dry the incriminated material
- Increase the temperature of the heating plate.
- Print on specific tape or glue.
- Lower the Z offset stepping

Fragilities on Top & Bottom surfaces



Symptoms: The horizontal faces are too thin and brittle.

Possible causes:

- Lack of material thickness above and below an object printed with a sparse fill. The deposited threads have too few support points and collapse between the ribs of the filling.

Proposed fix:

- Put at least 2 or 3 completely filled layers ("Solid layers" parameter in the slicer) for the "top" and "bottom" surfaces.
- Increase the infill of your object.

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Horizontal holes

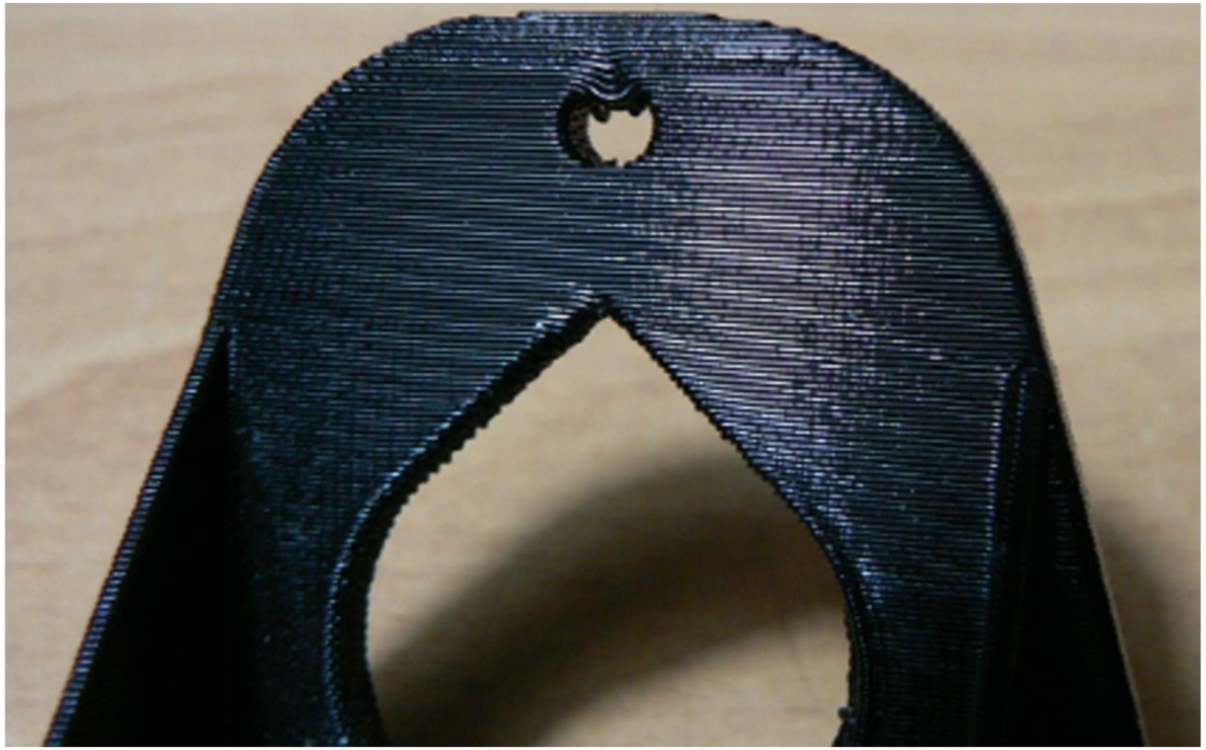
Symptoms: The top wires of a horizontal axis hole collapse on construction.

Possible causes:

- Zone too horizontal.
- Poor coherence between nozzle temperature, cooling of the deposited wire and speed.

Proposed fix:

- Reduce or remove this overhang area by modifying the geometry of the 3D file. Example on the large holes in the photo, in the shape of a drop of water rather than a cylindrical one.
- Add print supports below this area if the overhang is too much for the 3D printer to handle.
- Avoid slowing down too much in this area, even if the layer print time is low.



Color variation / transparence

Symptoms: The color or transparency of the material varies depending on the sections during 3D printing.

Possible causes:

- Different crystallizations of the material due to different cooling rates.
- The radiation from the nozzle can have an impact on the thermal cycle of the previous layer and thus vary its appearance.
- The deposited layer is too hot because the lower layer has not had time to cool.
- Attention, the physical and mechanical properties of the part can vary according to these crystallization differences!

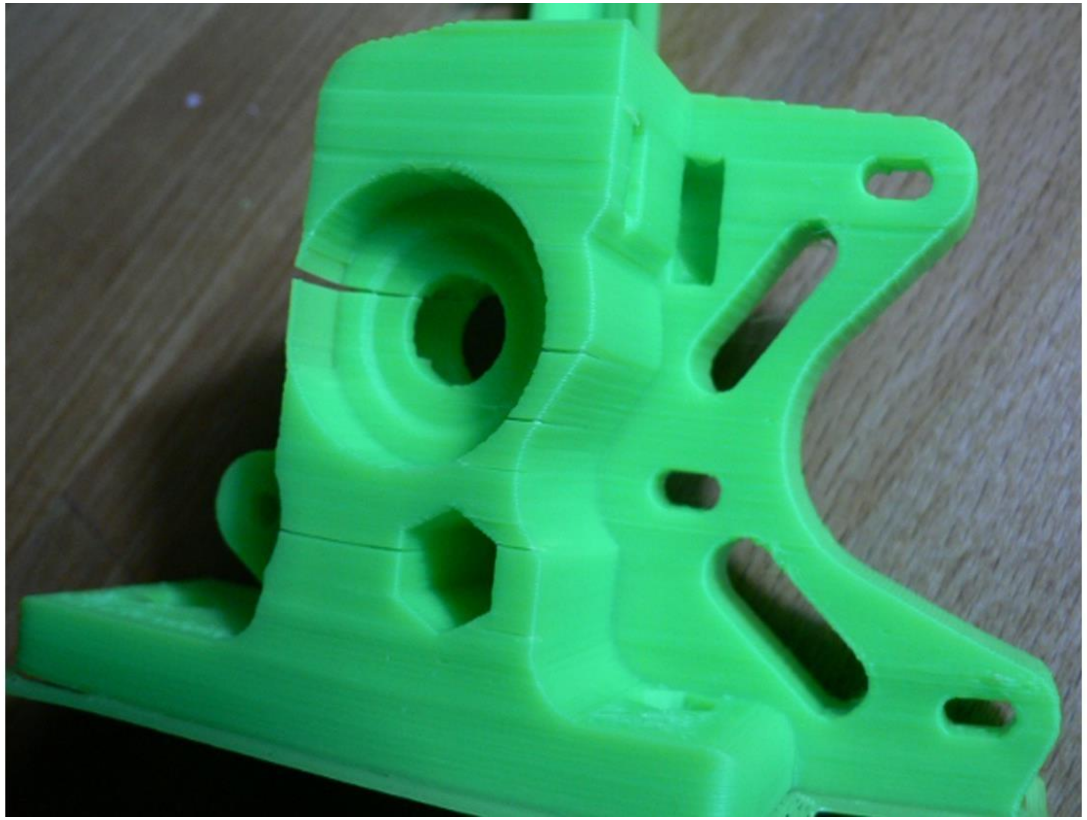
Proposed fix:

- Better manage cooling via the slicer parameters: vary the power of the fan according to the cooling time of a slice or slow down the printing speed in proportion to the surface of the slice.
- Reduce the extrusion temperature to facilitate a faster and more homogeneous phase change.

Delamination / curling between layers

Symptoms: Some layers bend and significant cracks appear between the different layers of printing.

Possible causes:
- The curling phenomenon occurs between the layers.
- Cooling of the wire too fast at the nozzle outlet, it does not weld correctly to the previous layer.
- Significant contraction of the material then cooling or phase change.
- Certain materials extruded at high temperature (ABS, PC, etc.) may represent a significant contraction phenomenon.



Proposed fix:
- Modify the extrusion temperature.
- Change print material.
- Avoid blowing on dropped wire or reducing fan power.
- Enclose the construction area in an enclosure regulated at a temperature close to the glass transition of the material.

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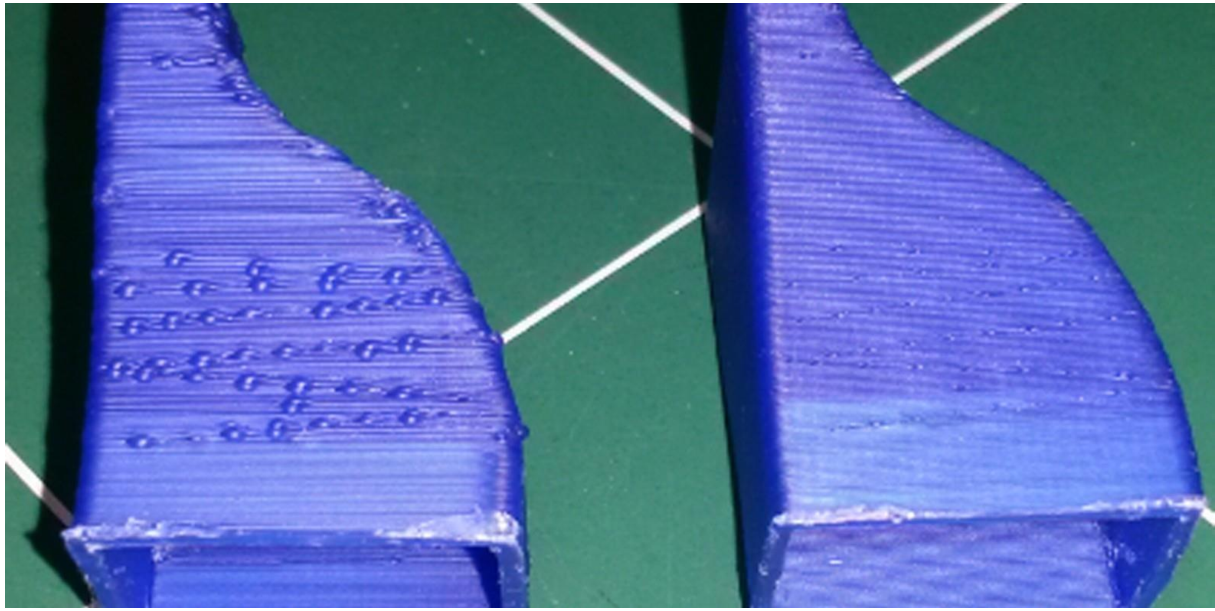
Droplets / Start & End points



Symptoms: Droplets of material are deposited at various points on the side surface of the 3D printed object.

Possible causes:

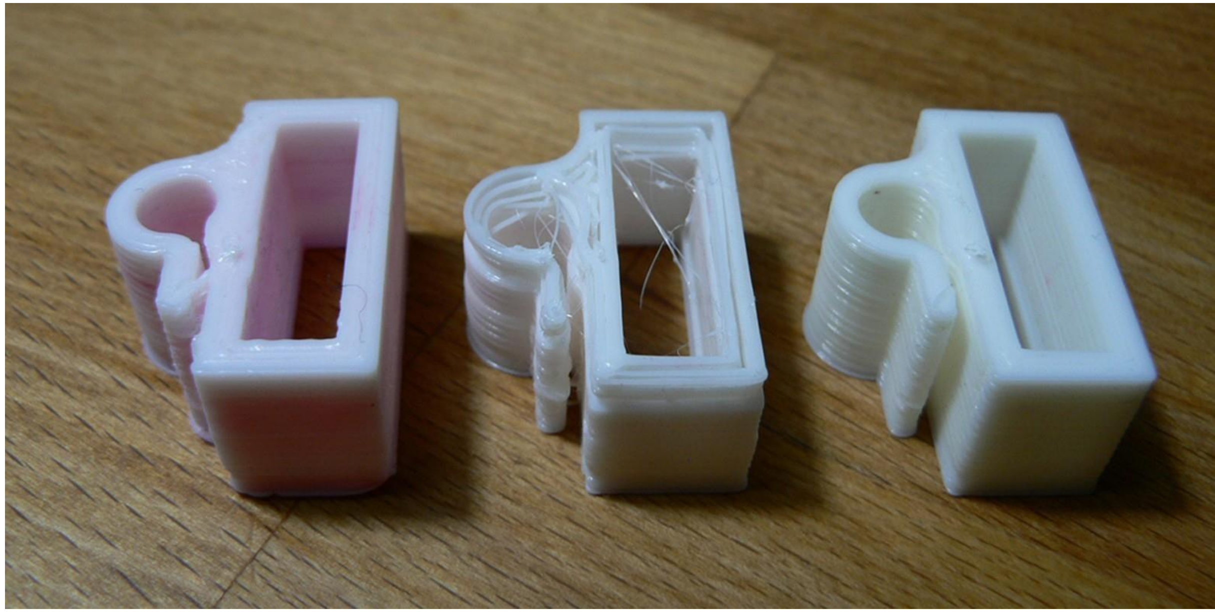
- Excess extrusion when resuming after stopping extrusion when moving from one point to another in the part, or when changing layers.

Proposed fix:

- Modify the retract parameter on the slicer

Management of retracts in Bowden

Symptoms: The Bowden extruder flows too much or not enough.



Possible causes:

- Filament shrinkage is insufficient to compensate for slack in the Bowden tube. Depending on the tube and filament diameters, and the length of tubing, the motor must pull a certain length of filament through the bends in the tube before the filament retracts from the hotend.

Proposed fix:

- Increase the retract distance in the slicer. The left part was printed with 1.5mm of retract, which was clearly insufficient. Passed to 6mm of retract, we obtain the central part. Too much shrinkage brings hot material back into the heat-break, the temperature of the heat-break gradually rises and the melting filament ends up getting stuck in the heat-break. The motor can no longer push it effectively. With a retract distance lowered to 4mm, we obtain the part on the right in the photo.

APTIME: Additive Process Technology Integration with Management and Entrepreneurship

Intellectual output 5: Polymer & 3D Printing – Environment & recyclability

https://www.farinia.com/fr/blog/limpact-environnemental-de-la-fabrication-additive-metallique

- Additive Manufacturing is a technology which is evolving quick, and may become a dominent process for polymer parts production. This may leads to **huge changes of environmental impacts**, with a lot of **positive points** but also some **negative ones**.

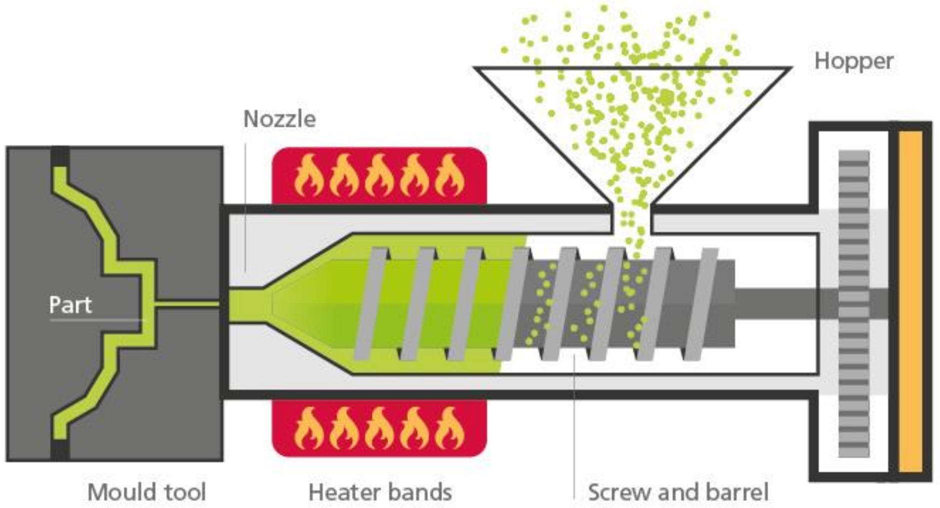
- The impact of 3D printing cannot be generalized, because it depends a lot on what type of part is produced, and on which technology. 3D printing technologies are evolving quickly so over the years the impact can be reduced a lot.

- Currently, injection molding and machining are the most used processes to produce a part. We are going to look in details at the differences between these three modes of production, and see their impact on the environment.

I. Current technologies for polymer parts production

Injection molding:

- Injection of melted polymer with a screw into a mould
- Possibility of producing serveral parts at once
- One mold is used for a lot of injections
- High rate production



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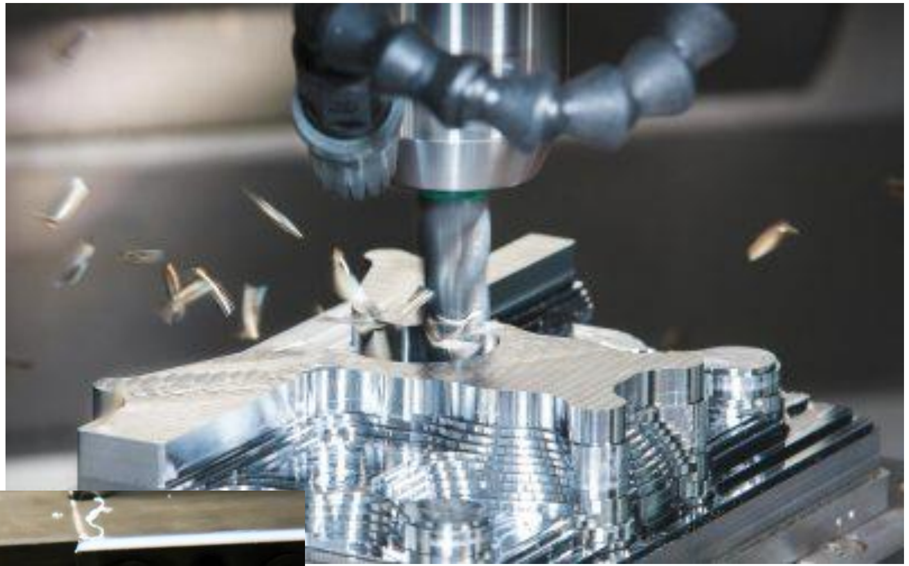
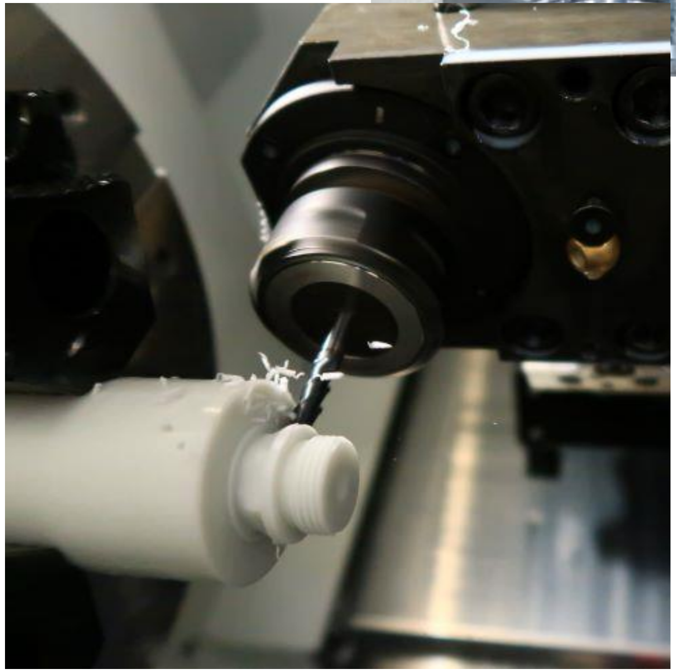
I. Current technologies for polymer parts production



Machining:

- A tool is removing material from an initial block
- Production of one part at once
- One tool is used for a lot of parts
- Average production rate



II. Life Cycle Analysis

The impact of a part on the environment can be estimate by running a Life Cycle Analysis (LCA). This analysis looking to each step of the life of the product, which are :

- Materials production
- Process
- Transport
- Lifetime
- End of life

Our aim is to compare the impact of these steps with classic parts production processes or additive manufacturing

a) Materials production

Nowadays, plastic materials are not respectful of the environment:

- Most of polymers are made from petrol transformation
- SLA resins are toxic while liquid, but become unharmful when solidified

The only material which can be consider as « green » is **PLA**, because it can be corn starch biobased, and biodegradable in industrial conditions.

b) Process

FDM :

- Electricity consumption for heating the polymer and moving axis, sometimes during dozens of hours for big parts
- ABS produces Volatile Organic Compounds (VOC) when heated
- Some supports may be needed for printing, considered as a waste of material
- One-part printing

SLA :

- Low electricity consumption for moving axis and turn on UV light
- Printing by sets of parts is possible
- No supports needed

b) Process

SLS :

- High energy consumption by the laser
- Non_used powder can be saved and used later
- Printing by sets of parts is possible

Liquid binder projection:

- Very low energy consumption
- Few printing wastes
- Printing by sets of parts is possible
- « Green materials » can be used

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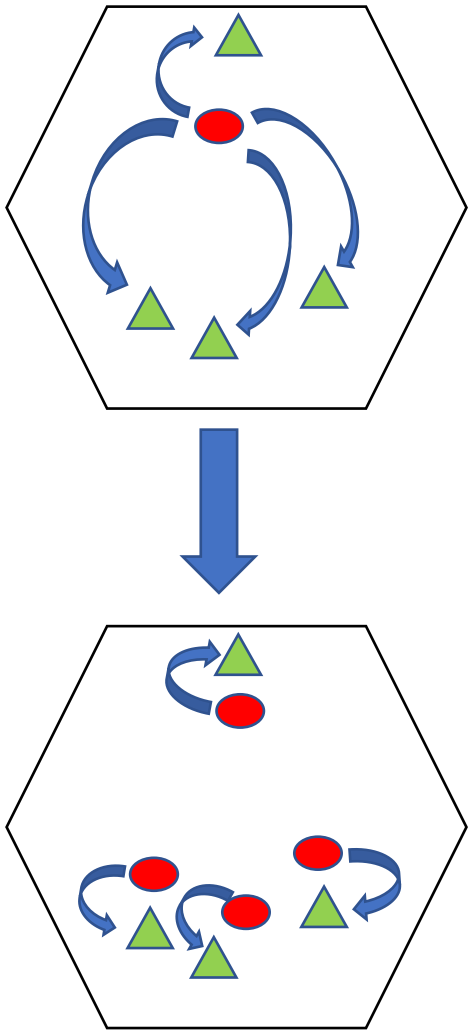
c) Transport

Classic processes for part manufactring :

- Big machines or molds are needed
- Few big factories producing the parts for the whole country/world
- Long distance transport from factory to store

Additive manufacturing :

- A lot of small production units dispersed all over the country/world
- Printing files can be sent to the right production unit
- Short distance delivery



d) Lifetime

After beeing printed, polymers are inert and unharmful for the environnement.
They are not toxic, they don't release VOC…

e) End of life

When the part is broken, or not useful anymore, its life ends. At this time, there are several possibilities:

- Part is thrown out into nature : still not toxic, but can be harmful if swallowed by animals for exemple
- Part is thrown to trash : it will be buried or burned, possibly releasing COV
- Part is sorted in order to be recycled or re-used

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e) End of life

Recycling :

- Parts produced with SLA, and solidified by UV light can’t be recycled
- Thermoplastics such as PLA and PET are easily recyclable if they are weel sorted out
- PLA is compostable in industrial conditions (60°C)
- ABS isn’t recycled

III. Short-time evolution of 3D printing

- Over the past 10 years, additive manufacturing has been improved, regarding size, quality, and printing duration of parts.
- Materials are also better known than before, so we have a large range of possibilities, depending on mechanical properties of the part.
- In the following years, it is safe to say that 3D printing is going to be used in a wider scale, resulting in an environmental impact change.

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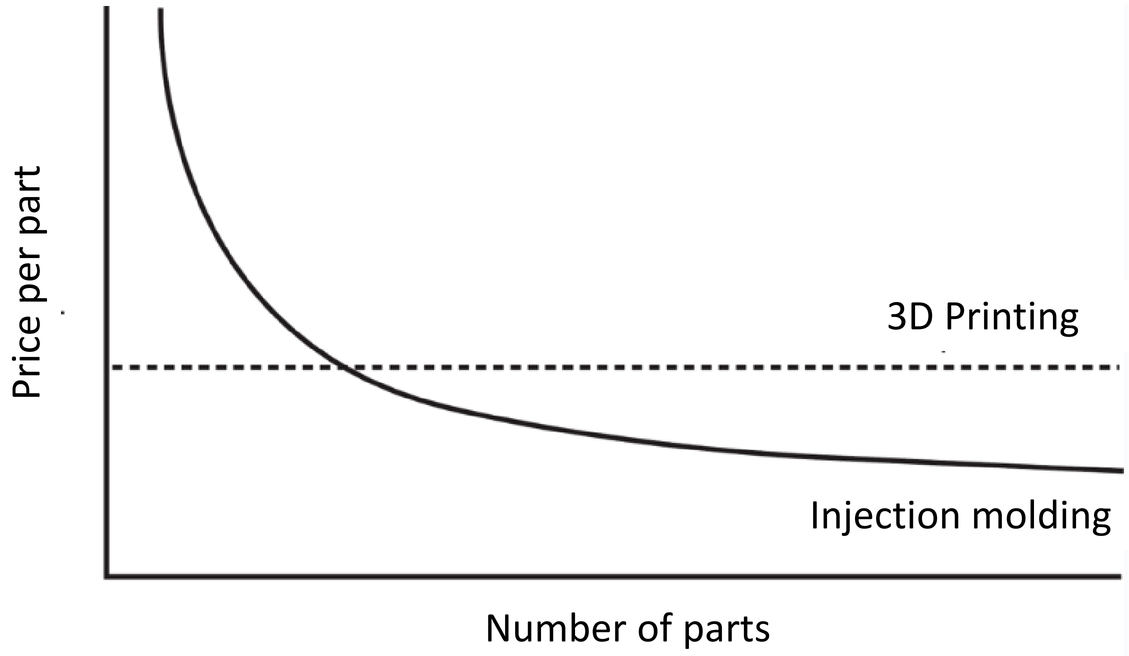
a) Diffusion in industry

If additive manufacturing is said to take a bigger space in industry, we have to understand that it will dépend on the sector of activity.

3D printing isn't competitive regarding the production of a big amount of parts with a low price, because molding injection and machining are cheaper. It is better suited for small series of parts of a price average to high.



b) Notions of quality, cost, and duration of part printing

There is an equilibrium to find between quality, cost an duration of the printing.

If the print speed increases, the quality may be lowered

If the print speed increases, the price will be lowered

→ It depends on the part printed and its use

The price of a printed is part should decrease over the years, meaning that the critical number of part will increase

IV. Environnemental impacts of 3D printing difusion

If estimations are right and 3D printing is going to be used a lot more than today, it will obviously have an impact on the environment, but it won't be an even increase or decrease. It will depend on the products produced.

The majority of the products are an assembly of several parts, each one produced by a different process, so we have to look to the new way to produce these products, and to which steps 3D printing will replace.

To have an example, we will compare 3D printing to machining and injection molding

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a) 3D printing compared to classic machining

Machining is the process which is more likely to be replaced bay 3D printing, but it shouldn’t have such a big impact on the environment, because machining represents only a low proportion of the industrial processes.

As 3D printing, it’s used for small series and prototyping, but the material cost is higher because this process remove material from an initial block. Additive manufacturing can also produce hollow parts, which reduces the production impact.

Depending on the geometry of the part, one process can be faster than the other, so it influences the choice of technology. As energy is a big factor of impact, quicker is the production, smaller is the impact.

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a) 3D printing compared to classic machining

All the 3D printing technology don't have the same impact, the highest being binder projection with 100% infill rate, and the lowest FDM with 10% infill rate. Machining is placed in between.

The impact is calculated with 4 main parameters : machine building, electricity consumption, material consumption and waste production.

For 3D printing, the main source of impact is electricity consumption, but for machining it's waste production. It means that going from one technology to an other may change the type of impact, but it doesn't necessarily reduce it.

b) 3D printing compared to injection molding

Injection molding of ABS is the most used process to produce polymer parts for public consumption, and the one having the lowest impact of the environment. PLA can also be used but it is less frequent.
The machine production, and configuration time, are divided by millions of part, so the impact per part is very low. But this only work for large series production.

3D printing using PLA have an impact per part 20% higher, remaining the same for one part as for a million. It means that 3D printing may be better than injection molding, but only below a certain number of parts produced. However, speaking of ABS printing, the impact can be ten times higher than injection molding.

The only printing technology that is better than injection is binder projection with salt, because the powder is linked by chimical way, and not by fusion, so the energy consumption is 70% lower. The problem is that the quality of parts produced with salt is also lower than those produced with injection molding.

V. Environmental sustainability of additive manufacturing

Additive manufacturing can be a source of reduction of environment impact, but not in the way we often think.

In the common opinion, additive manufacturing is able to almost suppress material waste and transport of parts, but these points should remain the same or only be a bit reduced.

In fact, 3D printing is more likely to produce closer to what is needed, to give access to a wider range of material to produce part, and reducing the using cost of some materials.

Additive manufacturing can use biosourced and compostable polymers, which can help to solve the wastes problems.

Also, it can help the society by give access to production proces to a larger range of people.

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a) Misconceptions about the environmental benefits of 3D printing

Transport reduction : A lot of small production units dispersed over the country → Less transport?

- Only for single material products
- Several parts need to be assembled → Transport to an assembly factory
- Transport for source material is increased
- Transport isn't the biggest impact of a product lifetime

Material waste suppression :

- Only with FDM for few parts that don't need supports
- SLA and binder projection can produce with <1% of waste
- FDM supports can sometimes represent more material than the part itself : >50% of waste
- SLS generate waste because not all the non-solidified material is re-usable
- FDM material reel is consider as a waste
- Injection molding is very efficient between 5% and 10%
- Reduce waste may lead to increase energy consumption

b) Green materials

Additive manufacturing is likely to increase the amount of « sustainable » materials, because they couldn’t be used with classic production processes, but 3D printing may unlock some possibilities.
Hopefully, we will see new production materials, using « ingredients » available in large amount, non toxic and renewable.
PLA is currently the only biopolymer widely used for 3D printing, due to its physical properties.

There is an economic motivation to look for green materials for 3D printing : the material versatility.
In classic manufacturing, only few materials are used, because of configuration costs. In additive manufacturing, these costs don’t exist. Materials can be switch easily.

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b) Green materials

There are still some problems to the utilisation of green materials:

- Compatibility material/technology : wood can't be used for SLA
- Commercial availability : salt and sawdust could technically be used but there isn't any retail distribution
- Substituability : Each materials have its own properties and isn't necessarily replacable by a green one (PLA and ABS)
- Quality of printing : Some recycled materials may have not the exact colour due to the recycling process, surface quality of parts printed with binder projection and salt is medium

→ For now, industrials don't want to change from their classic materials, but additive manufacturing could over the years replace them

b) Green materials

We can even think of modular materials, having different properties depending on their printing temperature, which could solve a lot of problems:

- A smaller amount of material can be used instead of a lot
- Toxicity could be easier to detect
- Composting and recycling may be imroved

The MIT worked on a material based on starch and cellulose, with a chemical polymerization and water. This material is biobased, biodegradable and uses renewable source material.
This polymer has variable properties, depending on the printing process

c) Recycling and composting

Currently, recycling is still rare because too expensive, and composting is only posible for biobased materials.

Recycling is also quite difficult because of the sorting of the materials. Each material has its own properties, and the quality of the recycled source material could be affected if there were two materials mixed together, meaning it couldn't be sold.
These mix can happen either because of a wrong sorting by the worker, or even when there is a change of material on a printer, both of them are melted together.

In order to overcome this sorting problem, predictable plastic source such as PET bottles could be found.

More, main of 3D printing materials are hard or even impossible to recycle.

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d) Reparation of broken parts

Repare broken parts in a product is the simplest way to reduce waste, and seems to be more sustainable.

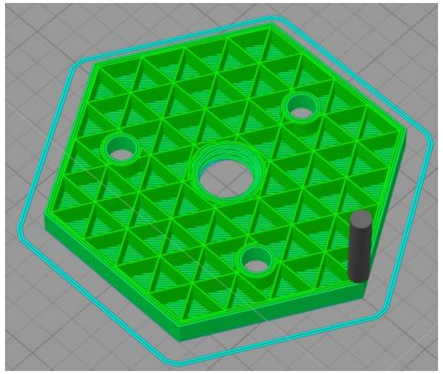
3D printing allows to produce a part which may not be possible to buy, and then to repare a product instead of throwing it and buying a new one. The only condition is to know how to create a 3D printing file, or to find it on internet.

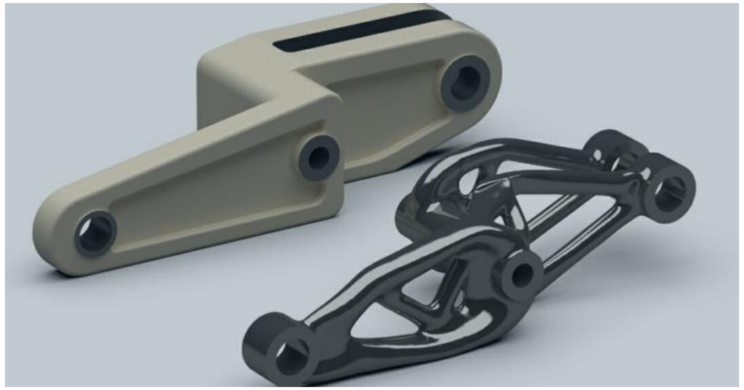
There is still a problem of Intellectual Property, for example with Thingiverse, and we may will have to pay to download it.

e) Energy savings during use

Indirect way to save energy with 3D printing → Weight reduction

A lot of part don't need to be fully filled, and have an excess of material.
To reduce the weight of a part, we have to possibilities : non-solid infill, or topological optimization





Regarding automotive industry or aeronautic industry, less weight means less energy consumption during use

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f) Technological improvments possibilities

In the following years, some improvments need to be realised to reduce environmental impact of additive manufacturing.

SLA:

- Impacts of materials : remove toxic chemicals, develop compostable biopolymers, reduce support materials
- Energy consumption : Print several parts at the same time, reduce printing duration, share printers to reduce inactive time

Binder projection:

- Impacts of materials : Develop compostable biopolymers, modulate material properties through printing process

FDM:

- Impacts of materials : Develop compostable biopolymers, non-solid infill, reduce support materials
- Energy consumption : Chemical solidification instead of thermal, reduce print duration, topologic optimization

g) Priority action points

Printer conception:

- High priority : Reduction of inactive time (sharing, quick cleaning), stanby mode with low energy consumption
- Medium priority : Chemical polymerization, better isolation, electronic motors
- Low priority : Actions in order to reduce material consumption and waste production

Materials:

- High priority : Develop compostable photopolymers for SLA, improve mechanical properties of biopolymers
- Medium priority : Chemical polymerization
- Low priority : Non-solidified polymer powder totally reusable, modular properties of materials

Conclusion

Additive manufacturing may revolutionize industrial manufacturing methods by replacing current technologies, and extend the access to production process.

Over the years, this replacement could have a lot of benifts for the industrial environment impact, but also some negative aspects. At the end, the ratio should be positive, but it depends on a lot of factors, including some ones we don’t already know.

The main source of environment impact for additive manufacturing are its energy consumption, its waste production, and the toxicity of materials used.

The diffusion of 3D printing will depend a lot on its technological evolution, and also on its price.

Conclusion

Additive manufacturing allows to put in phase environmental impacts with economical incitations, by making complexity cheaper and material price higher.

3D printing also have some indirect positive impacts as it helps to improve the reparation of broken products instead of throwing them, or reduce the weight of vehicles, saving energy.

Chapter 8: Practical courses

1. Programming
2. Manufacturing with FDM + SLA + Partners machines?
3. Post-processing